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DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

THE
LACCOLITHS OF THE BLACK HILLS

BY

THOMAS AUGUSTUS JAGGAR, Jr.

WITH A CHAPTER ON EXPERIMENTS ILLUSTRATING
INTRUSION AND EROSION

BY

ERNEST HOWE

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PART III—GENERAL GEOLOGY, ORE AND PHOSPHATE
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ERNEST HOWE

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THE LACCOLITHS OF THE BLACK HILLS.

By T. A. JAGGAR, Jr.

INTRODUCTION.

The description of igneous intrusions of the northern Black Hills in South Dakota and Wyoming contained in the following pages is the result of two field seasons' work in the mining district, spent in mapping the area comprised in the Sturgis and Spearfish quadrangles. This work was accomplished in the summers of 1898 and 1899 under the direction of Mr. S. F. Emmons, and in the fall of 1898 a reconnaissance was made by the writer to the northwest in order to study the outlying igneous bodies, more especially the group associated with the Bearlodge Range. Valuable field assistance was rendered by Messrs. J. M. Boutwell, J. D. Irving, and P. S. Smith. As a result of field observations, experimental studies were suggested. These were carried out in the laboratory of experimental geology at Harvard University by Mr. Ernest Howe, under the instruction of the writer, during the winter of 1898–99. Mr. Howe's results, which have proved interesting in comparison with field occurrences, are recorded in Chapter V.

It is not proposed to discuss the petrography of the intrusive rocks, but rather the structure and the origin of the intrusions. The region is remarkable chiefly for the systematic recurrence of certain distinct types of intrusive bodies so exposed by favorable uplift and erosion that many gradations from dike to sheet and from sheet to lens are revealed. In other words, there is here an opportunity for the study of dikes, stocks, sills, laccoliths, and irregular modifications of each of these, and exceptionally good exposures permit conclusions concerning dynamic conditions of intrusion which are supported by abundant field evidence. As the distribution and form of the igneous bodies are of great importance in connection with the occurrence of ores, and the history of intrusion is in some sense associated with that of mineralization, it seems well to describe in some detail these masses of igneous rock from the standpoint of dynamic geology.

DEFINITION OF TERMS.

The terms dike, stock, sill, and laccolith, as here used, need some definition. These definitions are not intended to be didactic, but are presented only to render intelligible the use of the words when applied to a region where many gradations occur between different kinds of igneous bodies.

A dike is an elongate intrusive igneous body occupying a fissure in any sort of rock, the walls of which at the time of intrusion were vertical or, if inclined, at angles nearer the vertical than the horizontal. A dike must have longitudinal extension much greater than its breadth, but may vary in thickness from an inch to several hundred feet. A dike may be irregular or may follow a sinuous course; it may be intruded between the beds of vertical or steeply inclined sediments; it frequently follows joint surfaces and has smooth and plane bounding walls. It must be noted that a flat igneous mass intruded between horizontal or nearly horizontal strata and subsequently upturned with them to a vertical position is not a dike, but a sill.

A stock is an intrusive mass of irregular ground plan, with bounding walls more or less upright at the time of intrusion; it differs from a dike in having no considerable longitudinal extension and in the absence of plane bounding walls. A stock occupies an irregular rent or cavity in the country rock, produced by disruption or fusion, or both, and if it occurs in sediments the fissure filled by the intrusion bears no definite relation to the stratigraphy or joints. The word stock is usually limited to bodies of considerable size, amounting in diameter to at least several hundred feet. Irregular intrusions intermediate in form between dike and stock may occur.

A sill is an intrusive sheet forced between strata which are horizontal or which, if tilted, lie at angles more nearly horizontal than vertical. The ideal sill splits strata apart on a single bedding plane and maintains a constant thickness. Sills in nature commonly break obliquely across bedding planes and may vary in thickness, though in the short distance in which they are exposed they need not show these characteristics. A sill may thin out to its border, or it may break upward along a joint plane to form a dike, or it may end against a fault surface. Transitions between dike and sill occur when a sill breaks upward at an angle of 45° or when a dike follows the bedding planes of strata inclined at that angle. The conduit that feeds a sill may be a vertical dike or an oblique, irregular, upward-breaking extension from another sill at a lower horizon.

A laccolith (formerly written laccolite) is a dome-shaped intrusion in horizontal strata or in strata more nearly horizontal than vertical. The ideal laccolith, like the ideal sill, splits strata on a single bedding plane; in nature laccoliths may break obliquely across bedding while still being guided in a general way by the sedimentary parting planes. The ideal laccolith is a radially symmetrical plano-convex lens with the convexity upward. Laccoliths in nature may be very unsymmetrical in ground plan and cross section and doubly convex. A laccolith may be a thickened extension of a sill; its conduit may be a stock, dike, inclined sill, or a combination of these, and it may fault and otherwise deform the strata about it. Transitions of the same sort as those described between dike and sill may occur between dike and laccolith. Transitions between sill and laccolith are of course common, the laccolith being a sill thickened locally or centrally and arching the strata lying in juxtaposition.

Commonly the intrusive magma which forms a laccolith has been believed capable of "lifting the load" above it. Such might be the case in strata of uniform flexibility, free from orogenic stress, subject to intrusion through ready-made conduits. When, however, those conduits are fault fissures and ruptures produced by strains incident to movements of mountain growth and so are permissive of igneous injection from below, the eruptive liquids must be conceived to spread upward and outward chiefly along lines of weakness. The pressure exerted by a single igneous body among strata in such a case is but a minor feature, the path chosen by the lava marking the site of inherent tendencies to warp and buckle under greater orogenic stresses. Thrusting and swelling among shales, the laccolith arches beds "competent" to transmit pressure without stretching or flowing, but the dome once initiated, horizontal components producing lateral deformation become more and more efficient with increased flexure in the dome itself. The motion of uplift may be absorbed a short distance above the laccolith in lateral crumpling and faulting of the superjacent beds about the flanks of the dome, and if these are shales they are to a certain extent stretched on the crest and squeezed into the sags. Thus the laccolith below a great thickness of soft strata no more lifts the load than does a cube of pyrite or a calcite concretion[1] when crystallizing to deform the surrounding laminæ.

The term porphyry is used in the same sense with reference to an intrusive rock of porphyritic structure as "lava," applied to an extrusive. This use is prevalent in Western mining districts. The wide variation in mineralogical and chemical composition of Black Hills porphyries would make continual reference to specific types confusing to the reader, where the subject in hand deals purely with dynamic phenomena.

---

[1] Calcareous concretions of Kettle Point, Ontario, by R. A. Daly: Jour. Geol., Vol. VIII, No. 2, 1900, fig. 3, p. 138.

CHAPTER I.

GEOLOGY OF THE NORTHERN BLACK HILLS.

GENERAL STRUCTURE.

The Black Hills are well known to constitute the type of dome structure. They rise like an island in the midst of the Great Plains, with culminating peaks of pre-Cambrian granite intrusive in Algonkian schists, and these same schists and granite may be followed outward from the center of the Hills to an encircling escarpment of Paleozoic rocks dipping away on the northern, southern, and eastern sides, and mantling over the schists to form an extensive forested limestone plateau on the west. The center of activity of the younger porphyry intrusions is Terry Peak, a summit rising 7,069 feet above the sea, in the northern portion of the schist area exposed on the eastern side of the uplift. Northwest, north, and northeast of Terry Peak occur a large number of intrusive bodies in beds ranging from Algonkian to Benton Cretaceous. The structure and forms of these igneous bodies vary chiefly with the horizon of intrusion.

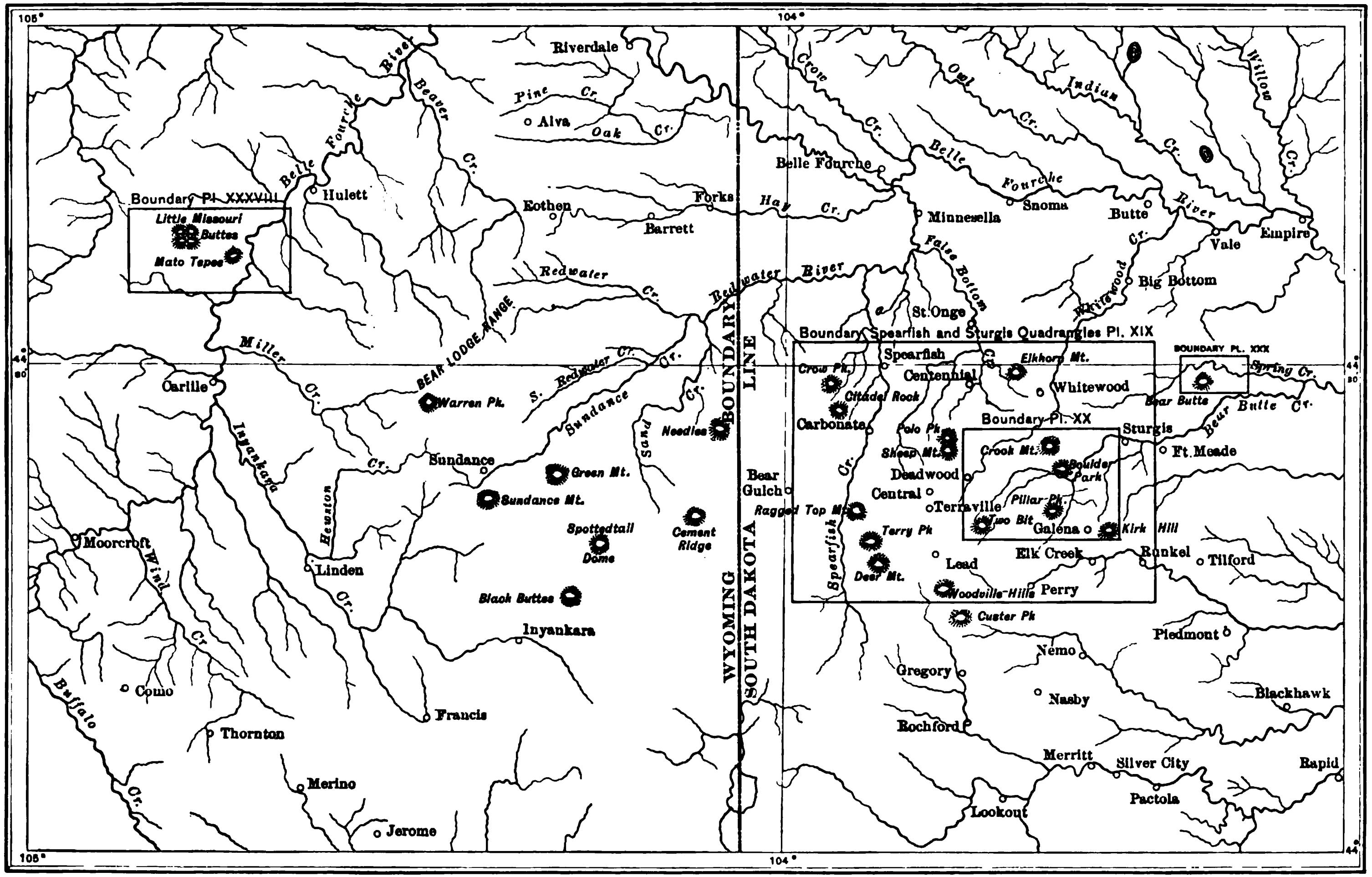
TOPOGRAPHY AND DRAINAGE.

The drainage of the northern Hills follows in general radial courses consequent upon the original slopes of the uplift as a whole. Where erosion has gone deepest this drainage has become modified by the development of valleys along the softer rocks, and, in consequence, subsequent valleys having courses concentric to the dome tend to follow along the strike of the Paleozoic and Mesozoic beds. The most conspicuous of these valleys is the well-known Red Valley, which forms a continuous depression around the Black Hills uplift.

DRAINAGE OF TERRY PEAK DISTRICT.

Four streams drain the Terry Peak eruptive center, flowing east, northeast, and north; these are Elk, Bear Butte, Whitewood, and Spearfish creeks. The drainage system of each of these has eroded away strata which capped igneous intrusives; and the porphyries, by reason of their more resistant quality, usually form prominent eminences above the general level.

The westernmost of the streams mentioned, Spearfish Creek, forms for 20 miles an impressive canyon in the limestone plateau, from which the stream emerges into the Red Valley at Spearfish. For a portion of its course this stream, which is to-day one of the most powerful in the Hills, flows along the contact of the Algonkian schists with the basal



INDEX MAP OF NORTHERN BLACK HILLS, SOUTH DAKOTA AND WYOMING.

Rectangles show approximate boundaries of areas included in Plates XIX, XX, XXX, and XXXVIII.

Scale: 1 inch=11⅓ miles.

beds of the Cambrian; above the mouth of Annie Creek the stream leaves the last outcrop of schist, and from here to the mouth of Robison Gulch, under Spearfish Peak, flows on Cambrian beds, cutting into porphyry masses at Annie, Squaw, and Rubicon gulches; then entering the zone of dipping Paleozoics, it progressively cuts its way across Silurian, Carboniferous, and Permian beds before emerging on the Triassic lowland of the Red Valley. (See Pls. XVIII and XIX.)

Whitewood and Bear Butte creeks, which flow to the northeast, traverse a more varied topography before they emerge from the Hills. They take their rise among Cambrian strata and porphyries, and their headwater branches have assisted in carving out the northern portion of the exposed Algonkian core of the Black Hills uplift. Through portions of their courses deep V-shaped gulches have been cut in the schist, and wall canyons in the Carboniferous limestone. Each formation in turn has its characteristic erosion form, which varies little throughout the northern Hills, and is usually directly dependent upon its relative capacity for resisting erosion. Indeed, the drainage as a whole, while retaining consequent courses in general for the master streams, shows many modifications by adjustment, more especially in the tributary branches, and occasionally striking instances of capture are evident.

Elk Creek, flowing east, drains on the south the high Algonkian plateau land which marks a portion of the area of maximum uplift. The upper portions of its course are characterized by broad meadow bottoms and gentle slopes from upland "flats" consisting of Cambrian or porphyry caps over schist. Where the stream enters the limestone, which is here of extraordinary thickness, a magnificent canyon with vertical walls rising sheer from 200 to 400 feet has been cut. Through this canyon the engineers of the Black Hills and Fort Pierre Railroad have built one of the most picturesque routes of travel in the country. Steaming through this impressive gorge the traveler moving eastward finds it difficult for some time to discover any considerable dip in the massive limestones, which retain for several miles the appearance of uniform thickness in the precipitous cliffs that wall in the torrent. Eventually, however, the canyon widens out and the limestone cliffs are replaced by bright-colored beds of the Minnelusa "alternate series," and then suddenly the characteristic gateway of Minnekahta limestone is passed and the train emerges into the broad lowland with its red marls and tilled fields.

TOPOGRAPHIC TYPES.

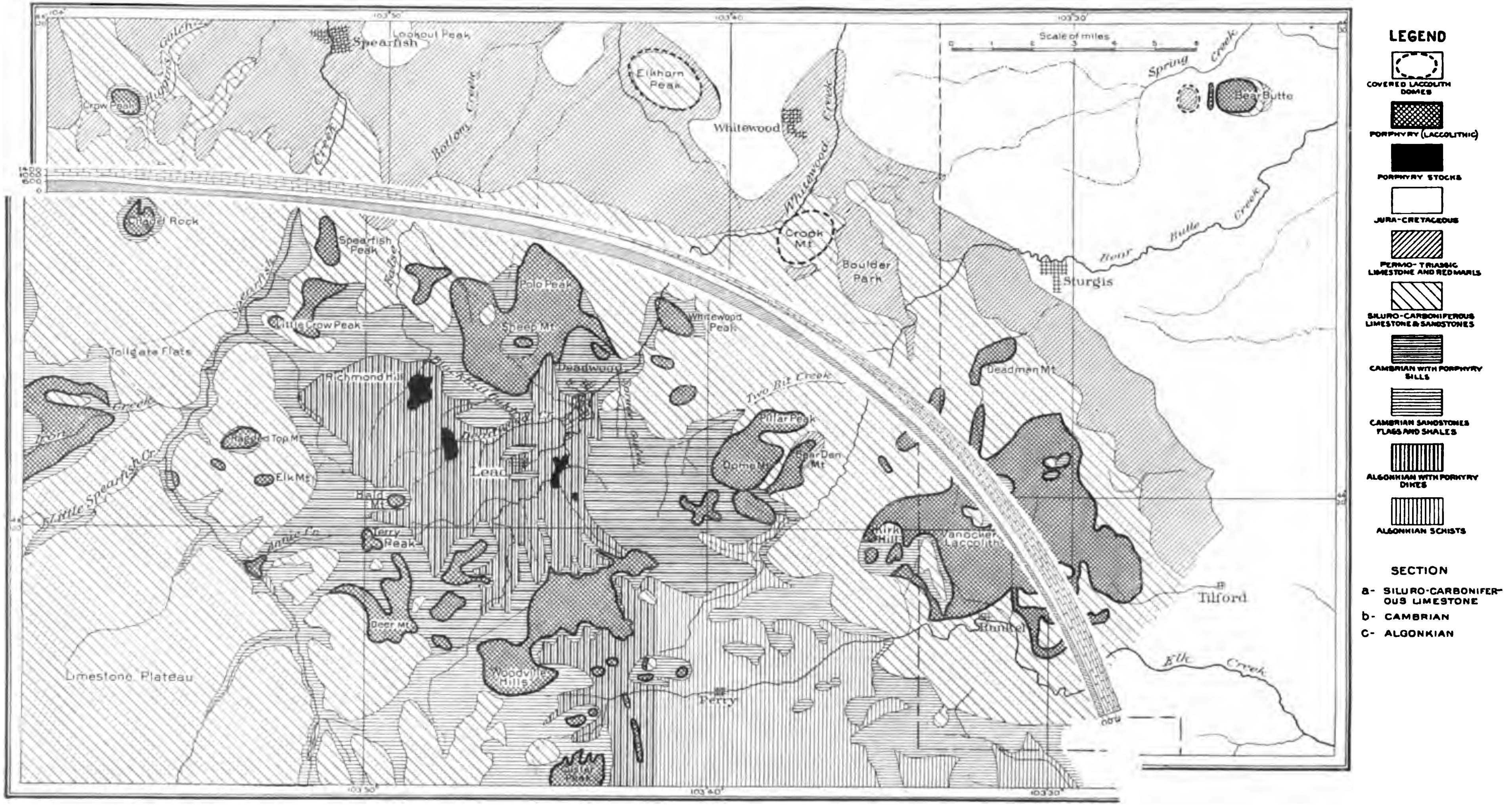
The Algonkian schists form flat uplands, and when they occur as massive upturned quartzites frequently jut out in colossal walls. Near Elk Creek one of these quartzite walls may be traced for miles, strongly resembling a dike. Elsewhere the Algonkian forms the bottoms of streams that have cut through the softer Cambrian beds, or it forms, with its characteristic steeply inclined banding, the slopes of steep gulches, like Whitewood Creek along the line of the Burlington Railroad. The many branches of the railway systems afford excellent sections of the Algonkian as they wind in and out along gullies and spurs to maintain their grade, and these railway branches and loops are now so numerous in the mining district as to form a conspicuous artificial feature in the topography; the same may be said of the innumerable tunnels and prospect holes with their dumps jutting out from the steep gulch slopes, the size of the dump an index of the depth of the digging. Thanks to this artificial "honeycomb" underground and the clean railway cuts above, much is now exposed to the geologist that was completely masked twenty years ago.

The Cambrian section where exposed beneath a protecting cover of limestone frequently forms wall cliffs of red and brown color, striped parallel to the stratification, one notable red band in the upper part of the formation being conspicuous in many places. The type locality occurs on the west side of Whitewood Creek just below Deadwood. Where its protecting limestone cover has been eroded away the Cambrian is likely to weather into rounded forest-covered hills of inconspicuous outcrop, like those occurring south of Elk Creek in the vicinity of Meadow Creek. Immediately beneath the Silurian limestone the Cambrian usually forms a bench, occasioned by the hard and salient "worm-eaten" (Scolithus) quartzite jutting out from beneath thick, soft, green shales (see fig. 60).

The Silurian limestone, in consequence of this relation and of another shale band above it, is frequently masked by talus, but, where its thickness is sufficient, forms a yellow bench, well shown in Whitewood Canyon on the route of the Fremont, Elkhorn and Missouri Valley Railroad. This bench is rarely seen west of Deadwood, and the Silurian is difficult to identify in Upper Spearfish Canyon. It occurs north of Annie Creek at several points in the canyon, at Crown Hill, and at Carbonate.

The Carboniferous, equivalent to the Madison limestone of the Rocky Mountains, is naturally the principal cliff maker, and its escarpment forms a conspicuous feature in the landscape everywhere. A more irregular and variegated cliff, colored purple, red, and white, and presenting one of the most picturesque color effects, is made by the Minnelusa sandstone, forming the "sand hills" encountered in driving out from the Hills just before reaching the Red Valley. The sandy soil of the Minnelusa frequently produces holes and sand in the roads which traverse this zone.

The Minnekahta limestone of the Permian forms one of the most conspicuous topographic features of the Hills. Dipping away with wonderful uniformity from the uplifted dome, the outflowing streams invariably cut through it a V-shaped gateway, making in the interstream spaces crescent-shaped scarps of the 30-foot limestone over the soft red sandstone that underlies it. The outer slope of the jointed limestone is usually washed bare and on the inner side of the Red



MAP SHOWING DISTRIBUTION OF DIKES, SILLS, AND LACCOLITHS, NORTHERN BLACK HILLS, SOUTH DAKOTA.

Valley forms what has been aptly called a tessellated pavement. The Red Beds themselves rarely present good exposures, though occasionally the streams which meander through the valley cut them into small buttes or mesas, capped by gypsum, which exhibit a bedded cross section. Such a section may be seen east of Whitewood.

Continuing outward from the Hills, the Jurassic beds outcrop on the inface of the Cretaceous escarpment that makes the outer wall of the Red Valley, and a conspicuous feature of these beds in the Sturgis district is a hard quartzite which forms angular blocks upon the slope. The crest of this slope is usually a rock face of coffee-colored or yellowish sandstone of Lower Cretaceous age. This sandstone slopes away toward irregular hills formed of other members of this series. The Dakota sandstone is the last hard, salient bed, and this in turn dips gently beneath a wide, arid tract of Benton black shale, the monotony of which is broken only by distant buttes of Niobrara limestone that appear upon the sky line far out across the plains.

STRATIGRAPHY.

DYNAMIC SIGNIFICANCE OF STRATIGRAPHY.

In the columnar section, fig. 60, are shown the average thickness and lithologic character of Paleozoic and Mesozoic rocks. In connection with the interpretation of dynamics of intrusion the distribution of thin-bedded and thick-bedded strata in the column is of great importance. Irving has shown the importance of shale beds as favorite horizons of intrusion; they are the readiest to yield to a viscous wedge of igneous matter. The accompanying columnar section shows three thick beds of soft material, the one at the top of the Cambrian, the Permo-Triassic red beds, and the Benton shales. The first underlies the most massive "competent"[1] member of the whole series—i. e. the great limestone, including both Silurian and Carboniferous. The lower red bed underlies the massive layer known as Minnekahta or purple limestone, which is overlain by easily deformed thick beds of red marl, while the soft, black Benton shales underlie the Niobrara limestone.

In addition to these three conspicuous shale horizons, other stratigraphic relations which would tend to influence intrusion are as follows: The Algonkian lamination abuts abruptly upward against the hard basal Cambrian quartzite or conglomerate, and this same lamination, while fairly uniform in its strike (NNW.), varies in its inclination east and west of the vertical, though it is prevailingly westerly in the Terry Peak region. An example of change in dip of the schists occurs at Central, in Deadwood Gulch, nearly opposite the De Smet open cut. Throughout the Cambrian, thin-bedded paper shales alternate with flags and sandstones, forming innumerable thin parting planes. Thin shales occur also above the Silurian and in the Minnelusa, Jura, and Lower Cretaceous.

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[1] The mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, 1892. "A thrusting layer firm enough to transmit the effective force" in strata folding under lateral compression is called a "competent" stratum. The same word may be applied to a stratum resistant to the upward progress of an intrusive magma, and thus competent to dome upward rather than split and mash like shale.

VARIATIONS IN THICKNESS.

The columnar section (fig. 60) shows average thickness for the northeastern part of the Black Hills. These figures are generalized from sections measured in Spearfish, Whitewood, Bear Butte, and Elk canyons. The progressive variation in this series of measurements, which is most significant in connection with the intrusives, is shown in the diagrammatic strike section (vertical exaggeration × 2.5) from northwest to southeast inserted on the map, Pl. XIX. From a thickness at Beaver Creek just west of the mapped area (Pl. XIX) of probably not more than 400 feet the Siluro-Carboniferous massive limestone, grouped as a single competent member, thickens to more than 700 feet in Spearfish Canyon. The Cambrian beds maintain throughout this region a rather uniform thickness, but probably diminish where the limestone is thickest. There is some evidence that the present course of Spearfish Canyon marks the axial region of a gentle syncline of deposition under the great limestone. For this reason the thicknesses in the section have been referred to an upper datum level, namely the top of the gray (Carboniferous) limestone.

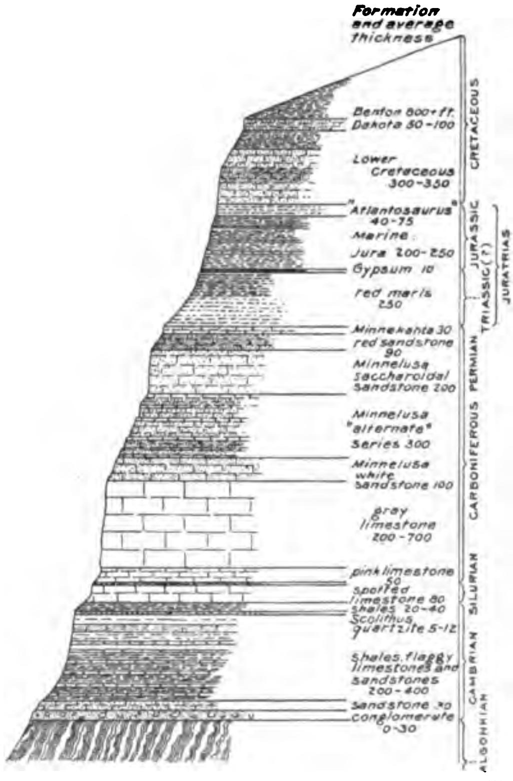


FIG. 60.—Generalized columnar section, northern Black Hills.

The Algonkian surface thus sectioned is seen to be warped into undulations. That some such undulations occur, and of much more pronounced relief than that represented in the section, is amply proved at several points. One of these is between Englewood and Nevada Gulch, where there is a rise in the Algonkian-Cambrian contact of 400 feet in a northwest direction—that is, tangent to the curvature of the elliptical area of the Black Hills uplift. Similarly the schist surface beneath the Cambrian at Brownville on upper Elk Creek shows a very rapid rise westward toward Woodville. Coarse Cambrian conglomerate fills hollows between ancient Algonkian quartzite reefs on the upland 4 miles southeast of Virginia on Bear Butte Creek, so that irregular relief in the original Algonkian surface, as well as irregularities induced by deformation, may be safely postulated. Warping of the schist surface in post-Paleozoic time probably proceeded largely by small slippings on lamination planes. These movements, when communicated to the flat-lying Cambrian beds above, produced innumerable small fractures—the "verticals" of the mines. The coincidence in trend between verticals and Algonkian lamination planes (NNW.) is remarkable. The thickness of the Algonkian is unknown, but there is good reason for supposing that its nearly vertical structure marks a series of isoclinal folds in which eventually some recurrent horizons may be identifiable. As is to be expected in the isoclinal structure, the schistosity usually conforms to the original bedding, but in places where the axial region of a fold is exposed, the lamination is seen to be distinctly transverse to the bedding, as in Deadwood Gulch near the town of Central.

East from Spearfish Canyon the great limestone shows a remarkable thinning, from 700 feet to a total thickness of probably not more than 100 feet on the flanks of Polo Mountain, a distance of 6 miles. The Cambrian thickens, but not in the same proportion; at Deadwood it has a thickness of between 400 and 500 feet. From Polo Peak, where the limestone stratigraphically overlies the greater porphyry masses of the Terry Peak complex, this massive member steadily thickens southeastward, reaching 300 feet at Whitewood Canyon, about 500 feet in Bear Butte Canyon, and probably more than 800 feet in Elk Creek Canyon. The Cambrian beds thicken at Bear Butte Creek, and then thin away to between 100 and 200 feet south of Elk Creek; and farther south, on the flanks of the Harney Range, the Cambrian almost disappears.

Summarizing this section from Beaver Creek to Elk Creek, the thick limestone in Spearfish Canyon separates two areas of igneous irruption and Algonkian elevation, namely, the Bald Mountain and Nigger Hill mining districts. The Terry Peak center of irruption underlies the thinnest portion of the limestone. The Two Bit region of maximum development of sills is where the Cambrian is thickest, and the Runkel region of large porphyry masses in and above the limestone is where the Cambrian thins and the limestone becomes thickest. A study of the map will show these relations. The Nigger Hill Algonkian area lies outside of the mapped area, on the west (see Pl. XIX).

COLUMNAR SECTION.

The paleontologic, lithologic, and topographic characters of the geologic column are best expressed in tabular form. Local formation names are avoided except where already in the literature of the Black Hills.

TABLE OF GEOLOGIC FORMATIONS IN NORTHERN BLACK HILLS.

PERIOD.	EPOCH.	FORMATION.	LITHOLOGIC CHARACTER.	TOPOGRAPHIC CHARACTER.	FOSSILS.
Pleistocene			Stream gravels	Fills saddles and hollows, usually divides; scattered bowlders on the plains.	
Eocene	Oligocene?	White River	Clays, white, pink, or buff. Small fragments of white rhyolite in conglomeratic layers.	Similar to above, but less abundant. Often under the Pleistocene gravels.	Vertebrate remains: Mesohippus, Ischyromys typus.
Cretaceous		Benton shale	Dark shales or clay	Plains	Fish scales and teeth.
		Dakota sandstone	Brown sandstone with limonitic nodules	Outer escarpments of Hills.	Plant remains.
		Lower Cretaceous	Sandstones, buff, white, and gray; limestones; colored clays; green shale; carbonaceous beds.	Crest of outer wall of Red Valley and irregular hills and escarpments.	Plants, cycads, etc.
Juratrias	Jurassic	"Atlantosaurus"	Fresh-water deposits, green shales, sandstones, and clays.	An inconspicuous bed in outer wall of Red Valley.	Saurian remains.
		Marine Jura	Buff marl, sandstone, oyster limestones, green and red clays, marls, and shales.	Lower beds in outer wall of Red Valley.	Belemnites, Ostrea, Trapezium, Pseudomonotis, Tancredia, Cardioceras, Lingula brevirostris.
	Triassic	"Red Beds"	Red marl with gypsum	Red Valley	

TABLE OF GEOLOGIC FORMATIONS IN NORTHERN BLACK HILLS—Continued.

PERIOD.	EPOCH.	FORMATION.	LITHOLOGIC CHARACTER.	TOPOGRAPHIC CHARACTER.	FOSSILS.
Carboniferous	Permian	Minnekahta limestone	Uniform purplish banded limestone, weathers white; strong bituminous odor when crushed.	Tessellated pavement on inner slope of Red Valley, escarpment and "gateways" of streams.	Bakewellia, Yoldia?, Edmondia*
		Lower red bed	Red sandstone, soft and marly	Inner slope of Minnekahta escarpment.	
		Minnelusa	Alternate limestones and thicker sandstones, somewhat colored.	Variegated striped cliffs and sandy hills.	
		Gray limestone, equivalent to Madison.	Massive limestone, gray, pink, or buff, sometimes cherty.	Massive cliffs, the greater escarpment.	Spirifer, Syringopora, Productus, Seminula, Zaphrentis, etc.
		Eocarboniferous, equivalent to Lowest Mississippian (Chouteau or Kinderhook).	Pink or purplish thin-bedded limestone with red iron-stained fossil mollusks. Purple or green shales below.	Frequently concealed beneath talus. Shows an apparent unconformity of erosion between it and the gray limestone above, though dip is accordant.	Fenestella, Orthothetes leptæna, Spirifer, Chonetes logani, Reticularia pecuKaris, Syringothyris carteri, crinoids.
Silurian		Equivalent to Upper Trenton.	Peculiar spotted massive limestone, usually buff with brown or reddish spots, sandy. Very large fossils.	Bench usually masked by talus.	Endoceras, Maclurea, Receptaculites, Halysites, Streptelasma, Lituites, Orthis, annelid trails, Buthotrephis, Murchisonia.
Cambrian		Equivalent to Middle Cambrian of the Rocky Mountains.	Conglomerate, quartzite, ferruginous sandstones, many alternations of green shale, limestone breccias, fucoidal limestone flags; at the top Scolithus sandstone or quartzite, and thick green shales.	Walls of recent canyons or old graded slopes; usually a pronounced bench.	Obolus, Hyolithes, Dicellomus, Asaphiscus, Olenoides, Ptychoparia, Acrotreta.
Algonkian			Mica, graphite, and hornblende schists, metamorphic quartzite and conglomerate, and some pre-Cambrian intrusives.	Flat-topped plateaus and headwater valley bottoms.	

The Pleistocene and Tertiary formations have an indefinite thickness, occurring, as they do, only in the form of eroded remnants. Tertiary occurs as white clay in the basin where Lead has been built and in the saddles between neighboring hills. This clay contains fossil vertebrates, and also fragments of porphyry, hence is the product of erosion after the porphyries were intruded. This is further proved by the fact that the clays are deposited in a topography eroded far below the present porphyry summits. The material here called Pleistocene consists of rounded stream bowlders and gravel occurring in masses sometimes 50 to 100 feet thick, usually filling divides between the present streams. These remnants show the location of more considerable deposits of the same sort along ancient stream channels. The courses of these ancient streams in several cases show a significant relation to elbows of capture and valley trends which mark the changes the drainage has undergone. (See Pl. XX.)

INTRUSIVE PORPHYRIES.

LITHOLOGY.

The porphyries vary in kind from rhyolite, diorite-porphyry, and syenite-porphyry to more alkaline rocks which may be classed as phonolites and grorudites. Irving has described many of the types, and there is here a remarkable series of gradations which renders the region exceptionally favorable for study of magmatic differentiation. He has distinguished the following families:

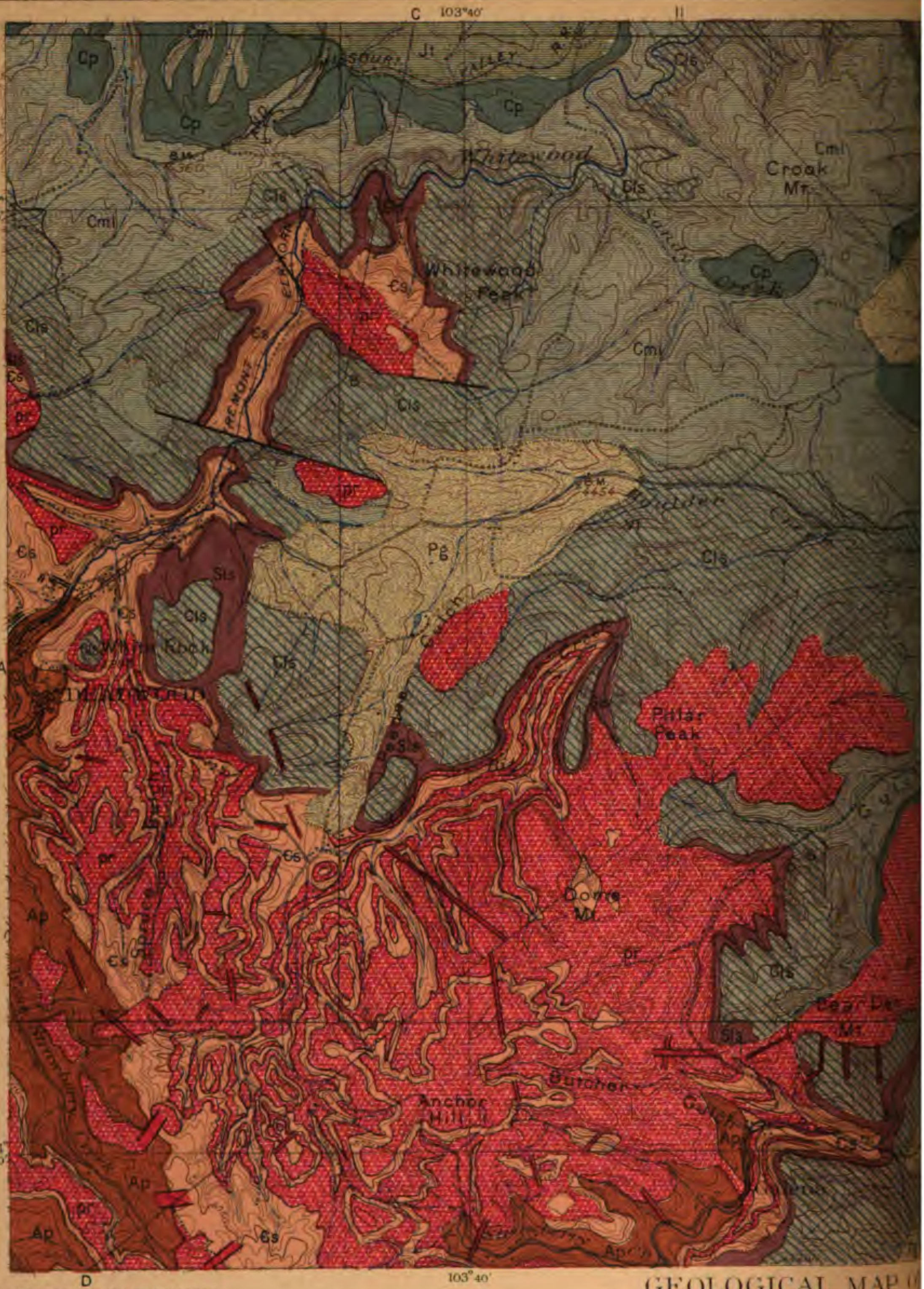
Grorudite.—Highly alkaline rocks containing orthoclase, quartz, ægirine-augite, and ægirine. In some types accessory albite, microcline, and biotite. Localities: Terry Peak, Bald Mountain, Elk Mountain, Lost Camp Creek, Annie Creek, sheet on the Burlington Railroad east of Terry Peak, and in the Sunset Mine.

Phonolite.—Rocks rich in soda, forming the more basic phase of the grorudites. Composed of orthoclase, anorthoclase, microcline, ægirine-augite, ægirine, nepheline, nosean with accessory haüyne, biotite, magnetite, titanite, melanite garnet, and possibly leucite. Localities: Ragged Top Mountain, Squaw and Annie creeks, Calamity Gulch, Mato Teepee, Green Mountain (peak next west of Bald Mountain), Whitetail Gulch, east slope of Bald Mountain, and False Bottom stock.

Rhyolite-porphyry and dacite.—Phenocrysts of orthoclase, plagioclase, and quartz in a fine-grained groundmass of quartz and feldspar; hornblende and biotite in varying amounts. Localities: Head of Squaw Creek, Foley Peak, Texana, Custer Peak, Butcher Gulch, Deadman laccolith, north side of Vanocker laccolith, Two Bit, Pluma, Bear Butte, lower portions of Sheep Mountain, Whitewood Canyon laccolith, dikes in many portions of Terry Peak district, Crow Peak, Inyankara, Sundance Mountain, and Warren Peaks.

Andesite-porphyry, diorite-porphyry, and diorite.—Porphyritic rocks containing phenocrysts of plagioclase, orthoclase, hornblende, and biotite in a fine-grained groundmass of plagioclase, quartz, and chlorite. The rock shows transitions to trachytic forms which may be called syenite-porphyry. Localities: Sills in Squaw Creek and in Ruby Basin, at the Needles, and in the region of the Vanocker laccolith.

Diorite forms the Deadwood Gulch stock above the town of Central. It is a gray



Topography by W. H. Herron
and Arthur Stiles

GEOLOGICAL MAP

LACCOLITHIC INT

EAST OF DEADWOOD, SOU

Geology by T. A. Jaggar Jr. assisted

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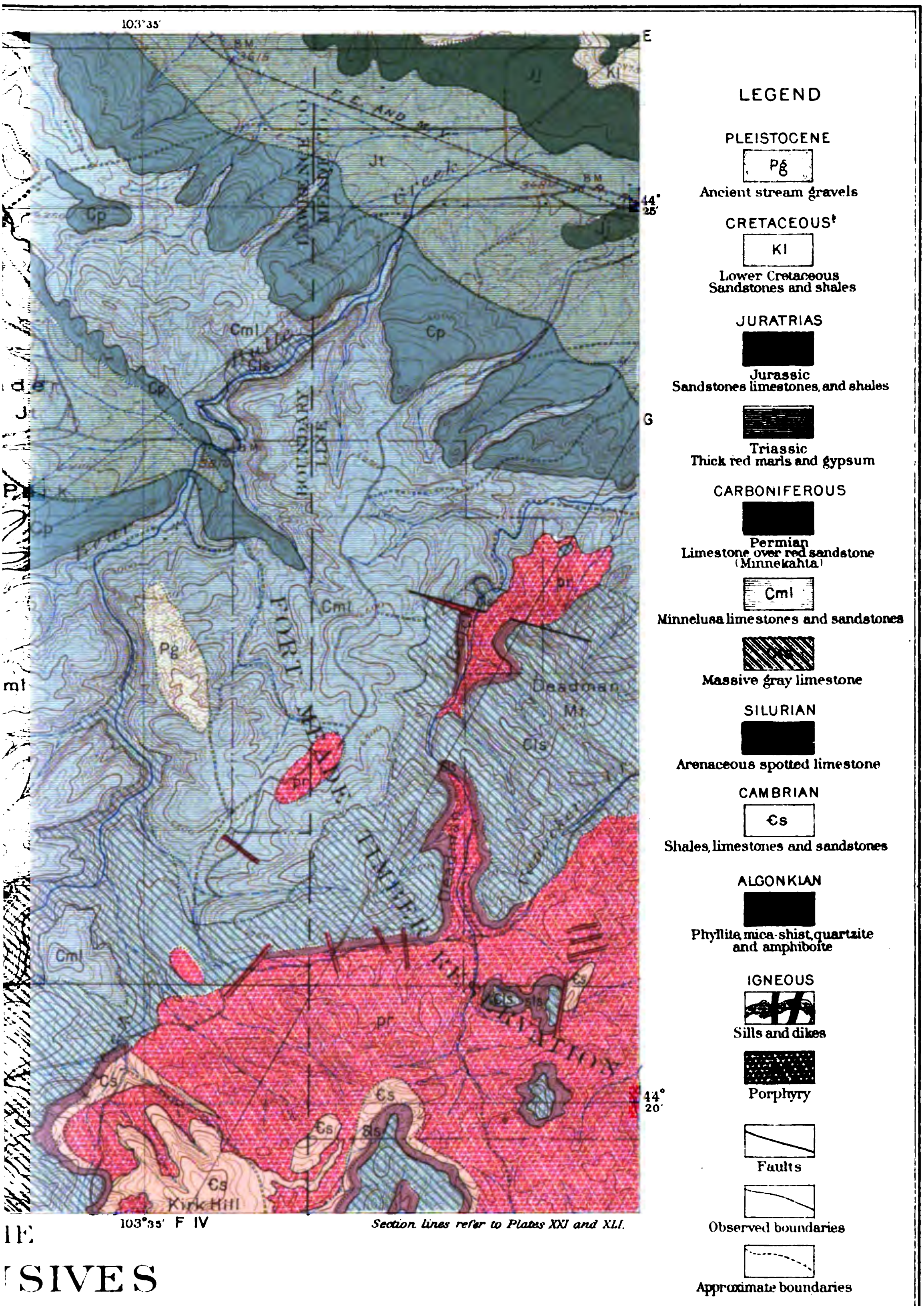

Section lines refer to Plates XXI and XLI.

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JULIUS BIEN & CO. LITH. N.Y.

rock of granitoid texture, showing a tendency, however, to automorphism in the component minerals; it contains hornblende, plagioclase, quartz, biotite, and accessory orthoclase.

Lamprophyre.—A basic rock in small dikes cutting the diorite-porphyry of the Needles, and again near the head of Iron Creek; it is composed of a fine automorphic aggregate of augite and feldspar, with accessory hornblende and magnetite. Irving considers it "the final and basic representative of the soda-rich magma that constitutes the principal Black Hills eruptive series."

It will be seen from the above that the rocks represented are not unlike many others that have been described from laccolithic mountains of the Rocky Mountain region,[1] and it is not possible at present to state positively whether a sharp distinction, marking different eruption periods, may be drawn between the phonolite-grorudite and the rhyolite-andesite magmas. The evidence points rather to a gradual transition between the two. The terms rhyolite and phonolite are unfortunately associated with extrusion, and it might be less confusing to speak of these rocks as granite-porphyries and monzonite-porphyries, but their structure would hardly warrant such a terminology. In distribution the dike region of the schist area contains both phonolitic and rhyolitic rocks; the sills of Two Bit and Squaw Creek districts are in general andesite-porphyry and diorite-porphyry; the outlying thick "plug-like" laccoliths, as well as a great portion of the greater Terry and Bearlodge complexes, are mostly rhyolite. But over the rhyolite on many hills, as Terry, Deer, Bald, and Sheep mountains, occur phonolitic caps, and the mass of Ragged Top, the Spearfish Peak group of laccoliths in the Carboniferous, and Mato Teepee are phonolite. The diorite magma is represented by a great stock in Deadwood Gulch, and its porphyry forms the mass of the Needles to the west and portions of the Vanocker laccolith to the east (see Pl. XVIII).

RELATIVE AGE OF PORPHYRIES.

Differences in relative age among the porphyries certainly occur if the transection of one dike by another may be considered conclusive evidence that the second is younger than the first. This evidence, however, has no conclusive value in a single instance, for one portion of a magma might readily crystallize and split up to receive, later, injections of differentiated material originally part of the same igneous fluid. Between the solidifying of No. 1 and the injection of No. 2 the time elapsed may not have been great enough to cover the whole period of solidification of the larger masses of No. 1. If this were true a later injection of No. 1 might elsewhere cut an already solidified body of No. 2, in which case the apparent relations in age would be reversed.

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[1] See The laccolitic mountain groups of Colorado, Utah, and Arizona, by Whitman Cross: Fourteenth Ann. Rept. U. S. Geol. Survey, Part II, 1893. Also, Judith Mountains of Montana, by Weed and Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898.

The preponderance of evidence would seem to show that in the Black Hills the phonolite magma as a whole is younger than the rhyolite magma. Within each of these there is probably a gradation from basic to acid, but fine distinctions are not warranted by the petrographic study hitherto given to these rocks.

Many occurrences in the field of dikes of one kind of porphyry cutting another may be cited. In the Two Bit district the greater masses of syenite-porphyry vary from a hornblende facies to one characterized chiefly by large orthoclase phenocrysts with poikilitic intergrowths of plagioclase and other minerals. Dikes which cut this rock are in general like the mass of Bear Den Mountain, which is an outlying subordinate laccolith. (See Pl. XX.) They are of trachytic, light-colored porphyry, showing pink microcline phenocrysts. They may bear some relation to the phonolites. A similar rock with amber-colored feldspar phenocrysts in a gray matrix cuts fine-grained white aphanitic rhyolite in a small dike on the Terry branch of the Fremont, Elkhorn and Missouri Valley Railroad, on the spur between Fantail and Nevada gulches (fig. 61). Near Alkali Creek, on the divide from Vanocker Creek, numerous dikes cut the fine-grained rhyolite mass. These are a purplish trachytic rock with glassy feldspar phenocrysts showing striation (probably oligoclase) and a decomposed bisilicate. Other cases of the rock with phenocrystic pink (microcline) feldspar cutting the rocks of the rhyolite-andesite series occur on the spur south of White Rock, just above Deadwood, and on the ridge west of the head of Spruce Gulch. Near the sawmill north of Kirk Hill a gray rock containing much mica and yellow feldspars occurs as a dike cutting light-gray rhyolite which shows some hornblende. It is probable that these are mostly phonolitic rocks which cut rocks of the rhyolite-andesite magma. Irving has described four cases of phonolites cutting quartz-porphyries and diorite-porphyries.

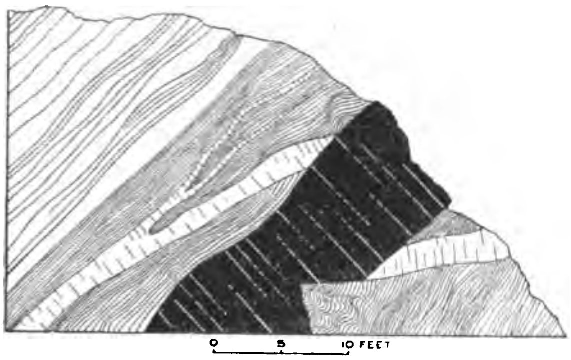

FIG. 61.—Green phonolite cutting rhyolite-porphyry, Fremont railroad, near Nevada Gulch.

A very unusual case (fig. 62) is shown in a section near Aztec on the Burlington Railroad (Spearfish branch). Here a mass of green phonolitic porphyry is apparently cut by an irregular swelling intrusion of white rhyolite of the fine-grained decomposed type so common in the region. Both occur, as shown, at a sloping dike contact with

Cambrian shales. All the evidence in this case would show the rhyolite to be the younger, or contemporaneous with the phonolite. The second alternative is the more probable. The two magmas may grade into each other, and in this case perhaps the green ægirine rock was still viscous when the stream of white rhyolite was injected through it. It is hoped that more extended study of the petrography of the region will throw light on these relations.

GEOLOGICAL AGE OF PORPHYRIES.

The geological age of the porphyries may be stated in only the most general terms. The Bear Butte and Little Missouri Buttes laccoliths were intruded into Benton Cretaceous and were unquestionably covered by Niobrara limestone. Jenney has found pebbles of Black Hills porphyries in the conglomerate at the base of the White River beds to the southeast, and similar fragments occur in the Tertiary beds at Lead. The Lead Tertiary clays (Oligocene?) are deposited in an old topography 1,800 feet below the present porphyry summit of Terry Peak and on divides 300 feet above the adjacent gulches. As these clays were flood-plain or lake (?) deposits, of mature stage in the early Tertiary dissection of the region, an additional 200 feet may be considered a most conservative estimate of height for the original porphyry upper limit of the Terry Peak Mountains. This porphyry at the time of its intrusion was covered by a thickness of strata not less than that of all the formations below the highest beds invaded; a minimum estimate would make this not less than 2,500 feet. This would imply a total thickness of rock eroded away above the present Tertiary beds at Lead of 4,500 feet (2,000 erosion + 2,500 thickness); accordingly, the later limital epoch of the intrusion period may be expressed as the beginning of a 4,500-foot erosion period prior to the Oligocene, while

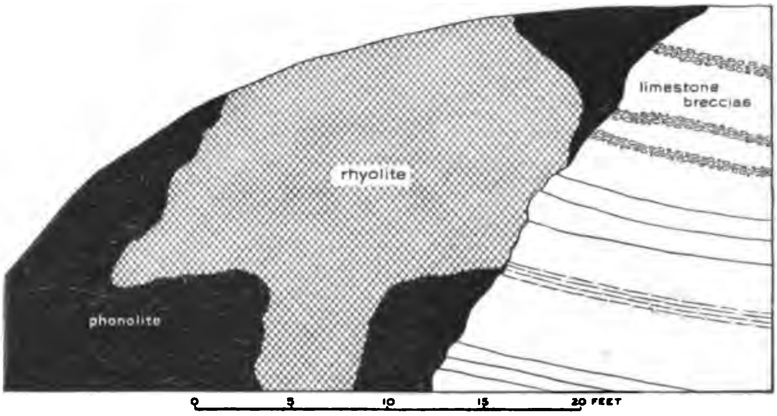

FIG. 62.—Rhyolite cutting green porphyry near Aztec.

the earlier limital epoch is the Niobrara. Between these there is the choice of Pierre, Fox Hills, Laramie, and Eocene times for the intrusion.

By analogy with the Rocky Mountains the greater uplift in the Black Hills probably took place after the close of the Laramie. The only evidence in the immediate vicinity of the Black Hills bearing on the question whether Laramie beds ever extended over the present site of the hills is the fact that they are tilted up by the Black Hills uplift on the west side; if they did so extend they may have attained a thickness of several thousand feet. The thickness of the Jura-Cretaceous below the Laramie is 4,000 feet.[1] If the first uplift of importance was in Eocene time and Laramie beds were present the erosion depth at Lead may be increased by several thousand feet. There are analogous intrusions of Eocene age in the Rocky Mountain district in sufficient number to render very probable the occurrence of igneous activity, concomitant with uplift, in the Black Hills at that time. That orogenic disturbances took place concomitant with intrusion is proved by the relation of the Algonkian-Cambrian contact to the porphyries at many places, the latter filling fault fissures. After the energetic erosion that led to deposition of Oligocene beds, and probably reduced the topography of the Hills to much lower relief than that of the present day, "there was a further uplift, which has given a very strong tilt to the White River deposits."[2] No porphyry now revealed can have accompanied this last uplift, which may still be in progress. By this last movement the Oligocene beds at Lead have been lifted and the present gulches have since been carved below them. The following is a summary of the evidence for the Eocene age of the eruptives:

Evidence from geology	Laccoliths in the Benton.
	Deformation concomitant with intrusion.
	Porphyry pebbles in Oligocene sediments.
Evidence from analogy	Post-Laramie uplift of Rocky Mountains.
	Post-Laramie intrusions of Rocky Mountains.
Evidence from physiography	Probable erosion of 6,000 to 8,000 feet of strata from above level of present Tertiary clay at Lead.

DISTRIBUTION OF IGNEOUS BODIES.

The intrusive rocks occur as stocks and dikes in the Algonkian schist, sills in the Cambrian shales where that formation is thick, and laccoliths, which in the Cambrian thin out into sills, but rise into thick domes of limited horizontal extension where the magma has broken through the massive Carboniferous limestone and escaped to higher horizons. These relations will be best understood by reference to the map, Pl. XIX, where Custer Peak, the Woodville Hills, Deer Mountain, Dome Mountain, and the Iron Creek mass represent laccoliths in the Cambrian associated with the broad sill district; this in turn surrounds the schist area of stocks and dikes. Outlying masses of steep domical form which have broken through the limestone are Ragged Top, Citadel Rock, Crow Peak, Whitewood Canyon laccolith, Pillar Peak, Bear Den Mountain, Deadman laccolith, Tilford laccolith, and Bear Butte. The great mass of the Vanocker laccolith on the east is an exceptionally large body which in part has broken across the limestone. To the north Crook Mountain and Elkhorn Peak are domes of Minnelusa sandstone, where erosion has not yet revealed the porphyry.

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[1] The writer is indebted to Mr. N. H. Darton for data and discussion on this question.

[2] Quoted from Mr. Darton, letter to the writer.

In the schist area many hundred dikes occur, trending usually about N. 30° W., parallel to the Algonkian lamination, and this trend in a general way corresponds with that of some of the larger laccolithic groups.,

Thus a line of porphyries may be drawn from Custer Peak to Crow Peak, from the Tilford laccolith to Elkhorn Peak, and from Two Bit to Polo Peak, possibly indicating an alignment of conduits beneath. At four points stocks have been indicated on the map, namely, at False Bottom Creek, Deadwood Gulch, Pluma, and a small mass east of West Strawberry Gulch; there are probably others in the hills west of Lead. The mass at Pluma is a great dike for a portion of its course, but becomes complicated with stocklike bodies, and is of such size as to warrant independent mapping. The area of sills in Cambrian shales has its best exposures on Two Bit Creek, Spruce Gulch, on the ridge southeast of Deadwood, on False Bottom Creek at Garden, along Squaw Creek, and on Annie Creek.

MECHANICS OF INTRUSION.

RELATION OF INTRUSION TO GREATER MOVEMENTS.

Many fresh cuts across contacts of porphyry with schist or Cambrian sediments afford instructive evidence with regard to the general relation of the intrusions to orogenic deformation. There are also miniature phenomena which throw light on large questions, in the same way that a laboratory experiment may be used to illustrate a principle. It has already been suggested (p. 173) that the work of an igneous body doming strata above it may be complicated with inherent tendencies in the strata to buckle under orogenic stress, and that without some such stresses fractures could not readily form to release the magma from the depths below. Throughout the Rocky Mountains igneous phenomena have accompanied colossal movements of uplift, folding, and faulting. Relative to these movements the igneous action was usually but an incident. It seems reasonable to suppose, then, that the first release of igneous matter among the Paleozoic sediments of the Black Hills took place by permission rather than by aggression. After entering the sediments doubtless the magmas under pressure acted locally as violent deforming agents. The schists, filled with dikes, were forced apart laterally, the Cambrian charged with sheets and laccoliths was greatly expanded in thickness and deformed horizontally, and the great limestone was domed up over the Terry Peak district as a whole and was locally pimpled and punctured by the small outlying masses. Thus intrusive action in the scheme of geologic deforming forces is both effect and cause; irruption is an effect of orogenic fracturing, a cause of localized doming and faulting. The fault fissures and fractures through which igneous material flowed contained necessarily more or less broken material, and the magma in its first uprush itself fractured and comminuted the rocks through which it passed. The result is a breccia, which is quite as much to be expected in association with an intrusive magma that has never reached the surface as are the characteristic tuffs and breccias of volcanic eruption. Such breccias are not wanting.

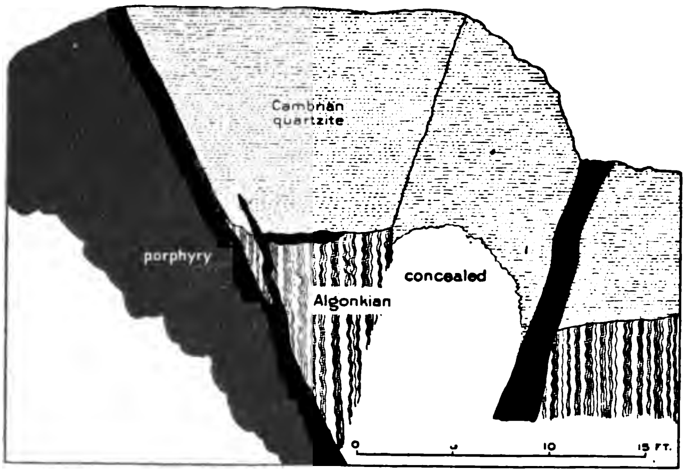

FIG. 63.—Contact of porphyry, Cambrian, and Algonkian, Nevada Gulch.

FAULTING AND BRECCIATION.

In a cut on the switch line of the Fremont, Elkhorn and Missouri Valley Railroad, on the north side of Nevada Gulch, is shown a section (fig. 63) that illustrates the faulting on a small scale so frequently observed in the Ruby Basin (a local name for the Bald Mountain mining district). The sketch is made looking north. There has been slipping approximately on lamination planes of the schist to form steps with the upthrow on the west, and this movement has been communicated to the Cambrian quartzite above. Possibly the 2-foot dike on the right follows one of the slipping planes. The principal fault plane in the schist is concealed by talus. The contact of a large dike on the western side of the exposure follows an oblique joint plane across both schist and quartzite, and a small stringer from this dike penetrates the schist and spreads along the basal contact of the Cambrian. This occurrence is similar to many others in the Golden Reward mines immediately to the south, and it is in part by such step faults that the Algonkian rises so rapidly from Englewood to Nevada Gulch.

Breccias are very abundant throughout the porphyry district, but by reason of their friable nature they are naturally concealed by talus. A breccia occurring under porphyry in Hidden Treasure Gulch, and again at the head of the Homestake open cut at Lead, contains angular or roundish fragments of a banded white substance which is probably largely whitened and silicified schist. There are also fragments of graphitic schists and quartz in a brown, muddy matrix. A similar breccia containing coarse angular fragments of hematitic schist and black graphite schist occurs near Garden. At the contact of a dike near Texana two varieties of breccia occur. One is very friable and is composed of a carbonaceous mud (evidently derived from the adjacent graphitic schist) filled with angular white fragments. The second variety contains closely crowded fragments of graphite and talc-schist and shows very little of a white chalky matrix. A specimen collected on the eastern spur of Bald Mountain shows fine-grained, white, subangular fragments (rhyolite?) in a greenish-gray matrix. The rock is hard, but contains rusty vesicular cavities. Similar breccias have been collected in Squaw Creek, Gold Run, and under the columnar porphyry capping the hill at the head of the De

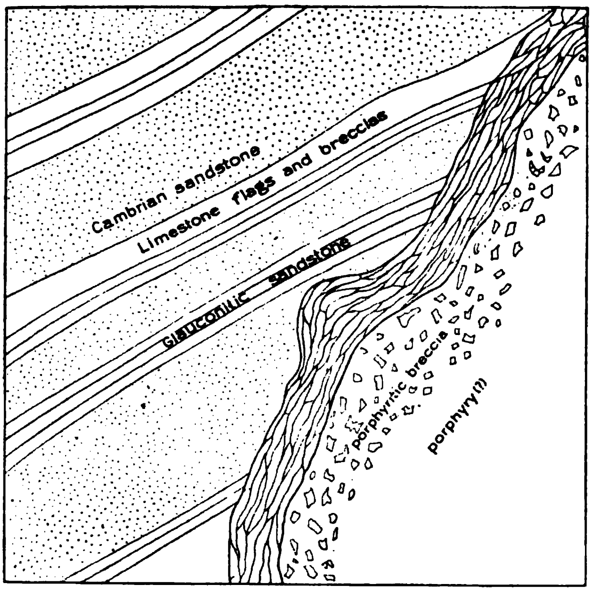

FIG. 64.—Section of contact of Cambrian sandstone and porphyry breccia near Brownsville.

Smet open cut. This relation of breccia to porphyry occurring immediately under laccolithic masses is a common one. A similar breccia containing very large fragments occurs in the Hoodoo mine, under the Union Hill laccolithic mass.

In fig. 64 is shown the contact, looking north, of a porphyry breccia with Cambrian glauconitic sandstones and limestones. The locality is a prospect hole in the southeastern end of a hill 1¼ miles northeast of Brownsville. On knolls south of this outcrop a peculiar porphyry breccia occurs in scattered outcrops for three-quarters of a mile. The breccia is probably at the base of an extension of the Custer Peak laccolith (see map, Pl. XIX), of which these outcrops are isolated remnants. A friction breccia occurs along the Cambrian contact, composed of reddish sandy material. The porphyry breccia is pink, made up of angular fragments of banded white or pinkish rock that appears to be an altered sediment. There are many small fragments of chalcedonic substance, quartz, and pieces of dark porphyritic rocks in a hard dark-red matrix, of which very little is present. The matrix is crowded with small white angular fragments. The rock as a whole is hard and trachytic, porous, and contains rusty cavities.

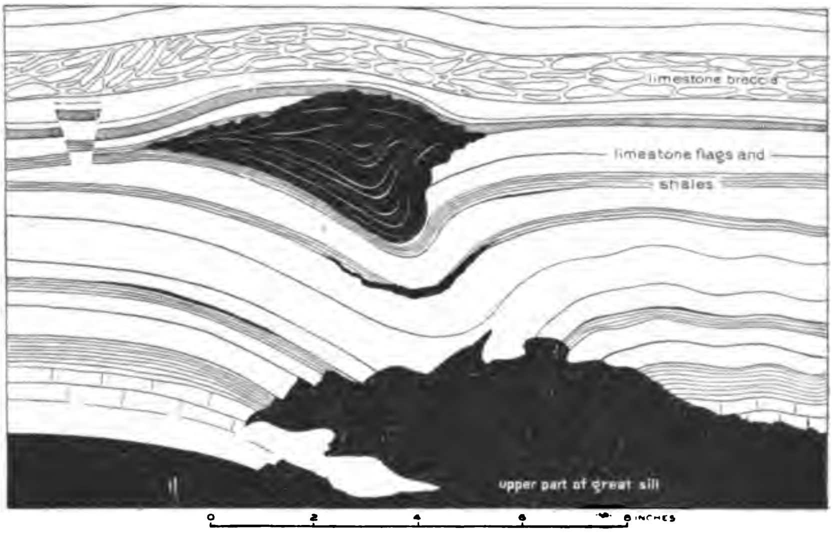

FIG. 65.—Miniature laccolith, Galena.

That these breccias are actually contemporaneous with the igneous rock is proved by the frequent occurrence, in the matrix, of crystalline structure identical with that of the porphyry. Such breccias occur as a large dike west of upper Two Bit Creek, and on the west side of Pillar Peak. In the last case distinct feldspar phenocrysts may be seen in the matrix of the breccia. A limestone breccia from a porphyry contact on the northwestern spur of Richmond Hill shows angular fragments of gray limestone and some pieces of Cambrian sandstone in a hard, yellowish-brown siliceous matrix; here the porphyry cuts Algonkian, Cambrian, and Carboniferous. In the Little Missouri Buttes and Mato Teepee occurs a tuffaceous breccia containing fragments of many of the rocks below the horizon of intrusion, and similar fragments occur in the heart of the porphyry as well. All the breccias mentioned are occasioned by and contained in igneous rock; they must not be confused with the limestone breccias of the Cambrian, which occur as lenticular bodies among the shales and are the product of deformation quite independent of the intrusives.

INTRUSION IN MINIATURE.

It will be seen that the essential features of the intrusion of sills and laccoliths are a molten mass impelled from below and strata variously shaly and massive. These features may occur in miniature as well as on a large scale, where in thin-bedded series alternate bands of shale and limestone occur, as in the Cambrian, and where the intrusive is sufficiently liquid to penetrate among the individual beds. Instructive miniature phenomena occur along contact walls of sills and dikes, and it is interesting to compare these phenomena with those of larger masses, which can never be so completely observed in cross section. The upper contact of a sill, 12 feet of which is exposed under the Sitting Bull mine, opposite the smelter at Galena, shows a number of irregular offshoots, and these locally deform the Cambrian bedding. The most striking of these, shown in fig. 65, is a miniature lens or lac colith of phonolite injected obliquely through a split in the strata above the greater sill, arching up the limestone flags above and *bending down those below*, so that they are fractured and gape open in contact with the greater mass of porphyry, and have spread apart to receive the injection of a little sill *under* the lenticular body. The greater mass

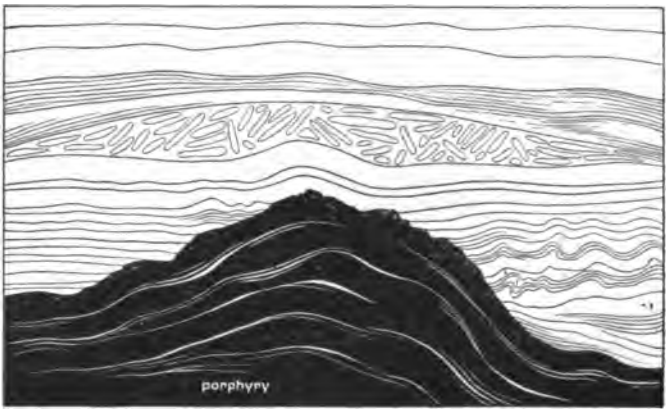

FIG. 66.—Upper contact of sill, Galena.

below was evidently liquid or viscous at the time the smaller mass opened its fissure. The latter, an offshoot of the greater mass, could not, by hydrostatic pressure alone, bend down the folia against the larger liquid body at a lower level. It seems probable that the down-bending was occasioned by differential contraction of the two masses while solidifying. Small faults and crumples at the side of these miniature domes are common along this contact, and frequently the cross section shows domelike projections from the greater sill (see figs. 66 and 67) which arch the beds above them and also cut across the flags, limestone breccias, and shales to a certain extent. The arching produced locally in this fashion is usually completely absorbed a foot or two above the eruptive, so that the higher beds are quite horizontal. Flow lines parallel to the contact are common, and in the case of the small lenticular body (fig. 65) they show that solidification on the walls was succeeded by an inflow of more of the fluid in progressively smaller cross section.

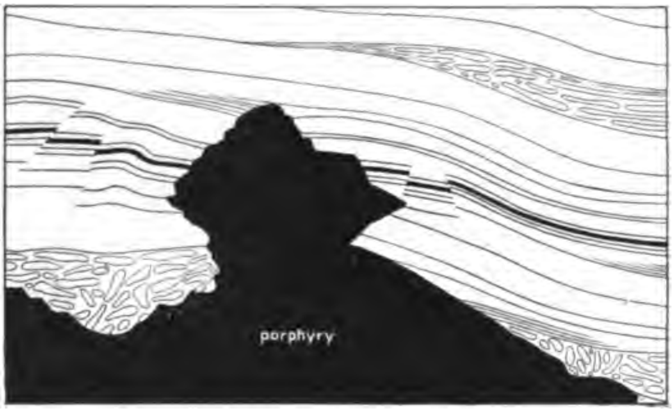

FIG. 67.—Upper contact of sill cutting limestone breccias, Galena.

PSEUDO-CONGLOMERATES.

Besides the dip away from the core of the Black Hills, which uniformly on the rim of the uplift indicates deformation of once horizontal sediments by forces other than those immediately generated by the recent intrusives, there is interesting evidence presented by the limestone breccias which are so abundant in the Cambrian. These occur in lenticular masses, sometimes merging into unbroken limestone flags interspersed among beds of green shale, the flags carrying trilobite fragments. These fragments of trilobites may also be seen in the flat or rounded "pebbles" of the limestone breccias, and this bars the possibility, suggested by Crosby,[1] that these breccias are conglomerates derived from an Algonkian limestone. The breccias in question were formed by crushing, accompanied in some cases by minute foldings of the limestone bands, the brittle laminæ breaking on the most acute flexures, or else breaking into flat pieces under the influence of pressure without any considerable flexure.

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[1] Proc. Bost. Soc. Nat. Hist., Vol. XXIII, p. 497.

Infiltration of waters which dissolved off the edges and corners of these broken fragments, later cemented the mass by depositing crystalline dolomite as a matrix for the pseudo-conglomerate. These "intraformational breccias" are abundant in the Two Bit district, where are also many sills and dikes of porphyry, and the question frequently arises in the field whether the deformation which fractured the limestone beds and the waters which cemented them were in any way associated with the intrusives. A negative answer to this question was clearly afforded by the upper contact of the sill figured (fig. 67). In the lenticular masses of limestone breccia here shown there are developed locally distinct folds, which pass by gradations into a breccia, holding fragments tilted at all angles, frequently without order or arrangement. Careful examination shows that often these may be resolved into former folds by joining the adjacent "pebbles." The work of solution and recrystallization on the fractured bends has nearly obliterated the original crumpling.

This locality, showing distinct crumpling occasioned by the porphyry in some of the beds and the ancient crumpling associated with the development of the pseudo-conglomerates, offers an excellent opportunity to test the question whether the porphyry was immediately the occasion of the brecciation. The contact shows distinctly that it was not. The limestone breccias are irregularly cut across by the porphyry both on the old folds and in places where all trace of folding has disappeared. In other cases where fragments of the breccia still remain horizontal the porphyry cuts across fragments and matrix alike. The unbrecciated limestone bands are occasionally folded and fractured by the porphyry, and on the fractures there is evidence of some recrystallization, so that it is not impossible that in places a newer breccia may owe its origin to deformation by intrusion; but in most cases the limestone breccias of the Cambrian were formed before the intrusives. This is further evidenced by the fact that these breccias occur in many parts of the Hills where the younger eruptives are absent, so that it is fair to conclude that the evidence indicates a period of deformation later than the Cambrian and earlier than the laccolithic intrusives. Similar limestone breccias occur less abundantly in the Carboniferous and Permian limestones. Weed has figured[1] a Cambrian limestone conglomerate from the Judith Mountains that in the photographic illustration is the exact counterpart of the Black Hills

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[1] Judith Mountains of Montana, by Weed and Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, Pl. LXX. Also, Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, Part III, 1900, Pl. XXXIX.

Cambrian beds. He believes it to have been formed on a shingly beach. The writer would suggest that possibly many supposed conglomerates may be intraformational breccias[1] composed of limestone fragments, formed by crushing and recrystallization of matrix, as described, rather than by uplift above sea level.

TOPOGRAPHY OF PORPHYRIES.

In general the topographic effect of the porphyries is to produce strong elevations, either by their own resistance to erosion or by concomitant induration of the adjacent sediments. Dikes in schist sometimes form conspicuous ledges, in other cases valleys, as in the case of the great dike at Pluma. Sills in the Cambrian may make slight benches on graded slopes or merely color bands in canyon walls. Laccoliths, according to the degree of their uncovering, may form hollows, hills, or mountains. Their physiography is discussed more fully in Chapter III.

The weathering of the fine-grained rhyolite is frequently more conspicuous than that of the phonolite, which in this district is notably fresh. Often the rhyolite shows a remarkable red staining in spherical shells throughout joint blocks; the large proportion of orthoclase accounts for the decomposition to kaolin. Frequently both quartz-porphyries and phonolites weather into spheres with concentric shells.

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[1] C. D. Walcott, Bull. Geol. Soc. America, Vol. V, pp. 191-198.

CHAPTER II.

LACCOLITHIC INTRUSIVES.

LITERATURE.

WARREN, HAYDEN, AND WINCHELL.

The earliest references to eruptive porphyry in the Black Hills occur in the reports of Warren,[1] Hayden,[2] and Winchell.[3] Warren mentioned Inyankara Peak, Bearlodge, the Little Missouri buttes, and Bears Peak (Bear Butte) as "volcanic." Hayden described Bear Butte as an "isolated protrusion" of igneous rock, surrounded by "disturbed beds forming annular ridges." Winchell visited Inyankara and Bear Butte; the former he described as a "single isolated outburst," greatly tilting and shattering the Carboniferous limestone, and but little affecting the Red Beds, which he believed unconformable above the Carboniferous rocks. The Bear Butte igneous mass he considered "thrust up after the deposition of the Carboniferous limestone. * * * As to the origin of this rock, it is undoubtedly eruptive." In the cases of both Bear Butte and Inyankara, Winchell notes the significant facts that "on the side toward the hills, in each case, the encircling ridge [of sediments] is low or wanting." None of the earlier explorers defined clearly the intrusive nature of the eruptive rocks.

NEWTON AND JENNEY.

In Newton and Jenney's more complete report[4] explicit descriptions are given of the several eruptive peaks, and these will be referred to in the following pages. Newton and Jenney recognized the intrusive nature of the igneous bodies, though the word "extrusion," used presumably in the unusual sense of irruption, or rushing in of igneous material, leads to some confusion in Newton's text. The following quotations will show the more general facts and theories developed by the Newton survey:

> The volcanic peaks are curiously limited within the region of survey by a parallel of latitude. The line of 44° 10′ divides the uplifted area * * * into equal parts.

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[1] Explorations in Nebraska and Dakota in 1855, 1856, 1857, by G. K. Warren, Engineer Department, U. S. A., Washington, 1875, p. 30.

[2] Geological Report of the Exploration of the Yellowstone and Missouri rivers, 1859-60, by F. V. Hayden, Washington, 1869, p. 42.

[3] Geological Report on the Black Hills, by N. H. Winchell; Reconnoissance of 1874, by Captain William Ludlow, Engineer Department, U. S. A., Washington, 1875, pp. 17, 37.

[4] Report on the Geology and Resources of the Black Hills of Dakota, by Henry Newton and Walter P. Jenney: U. S. Geog. and Geol. Surv. Rocky Mountain region, Washington, 1880, pp. 189, 219, 283.

> South of the line there is no volcanic peak either in the Hills area or in the vicinity; north of it they dot the country in every direction. They do not seem to bear toward one another any relation of distribution or intensity of igneous action. * * *
>
> The main points of eruption are as follows: Within the area of the Hills proper, Custer, Terry, and Crow peaks, and Black Butte [Spearfish Peak]; northeast of the hills, on the edge of the plain, Bear Butte; in the Red Valley, on the northwest side of the Hills, Inyankara, Sundance Hills, a nameless peak [Black Buttes] northeast of Inyankara, and Warren Peaks of the so-called Bear Lodge Range; on the Belle Fourche, Mato Teepee or Bear Lodge; and near the head of Little Missouri River, the Little Missouri buttes.
>
> Specimens from nearly all the prominent peaks have been critically examined by Mr. Caswell, who finds that they have a common facies, although some fall into the division of rhyolite and others into that of sanidin-trachyte [phonolite and ægirine rocks].
>
> In the structure of the peaks the first fact that strikes the observer is their uniformly conical shape. To this rule Bear Lodge is the only exception, and this, with its symmetrical columnar shape, is the most remarkable of all. The peaks appear to be merely pointed or conical waves of igneous rock forced upward through the sedimentary strata which are found disturbed and turned up around them only in their immediate vicinity. The metamorphism of the upturned strata is limited in extent, reaching only a few feet from their contact with the igneous rocks. There was observed no evidence of any overflow of the igneous matter, but it is confined exclusively to the cores of the peaks. The view that they are the cores of extinct volcanoes or centers of igneous overflow is scarcely warranted by the observed facts. * * * It would appear that the igneous peaks, instead of being the product of violent volcanic action, are situated at a great distance from the central and maximum region of igneous action; and that instead of the material being ejected with great violence and at such a temperature as to cause it to overflow readily, it was forced forward through the sedimentary strata under great pressure and at such a temperature as to make it plastic rather than fluid. The occurrence of these trachytic peaks appears like a great *pustular outbreak*[1] on the *surface* of the northern end of the Hills, whereby the deep-seated igneous forces were relieved, or like the appearance of bubbles on the *surface* of a kettle of boiling tar.
>
> The displacements associated with the igneous rocks modify the form and destroy the simplicity of the great displacement, but they have no discernible relation to it except the relation of superposition. Whether they were formed before or during or after the uprising of the great arch, there is nothing in their distribution to suggest that they are in any wise dependent upon it or closely related. Some of them are near the crest of the arch, some are where the rocks are steeply inclined at the sides of the arch, many are on the gentle slopes of the northern prolongation, and at least one is entirely outside of the hills. They are so much smaller than the protuberance on which they rest that they seem to be merely *superficial* phenomena—a sort of skin disease upon the *surface* of the tumor.

In the above theoretical discussion by Newton the word "surface" and reference to a "skin disease" show clearly that he conceived the porphyries to have been covered by no very deep mantle of sediments; the suggestion is of viscous fluids blistering a thin superficial layer. That this was his idea is borne out by his reconstruction of the Black Hills dome with a minimum of only 600 feet of strata above the Dakota sandstone (p. 205). Newton indicated the period in which the porphyries were intruded as lying between Benton Cretaceous, the strata invaded by Bear Butte, and White River Tertiary, where porphyry pebbles occur in a basal gravel deposit; but he states clearly that "the date of igneous activity is very far from established, and its relation to the uplift of the hills is not even determined."

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[1] The italics here and below are the reviewer's.

CROSBY AND CARPENTER.

Crosby, in 1888,[1] mentioned the presence of true laccoliths in the Black Hills. Carpenter,[2] in the same year, speaks of Bear Butte and Mato Teepee as "volcanic plugs." Of the others Carpenter writes as follows: "Some of these bodies appear to be true laccolites, among which may be mentioned Terry's Peak and Black Butte. Some upward bulges, like Little Sundance Mountain, resembling Gilbert's 'Pulpit Arch,' I formerly believed to mark the position of uncovered laccolites, but they probably marked only the position of plugs of volcanic matter like the Bear Lodge [Mato Teepee], and present, possibly, the same appearance that it did before the removal of the Cretaceous from around it."[3]

RUSSELL AND PIRSSON.

Russell (1896) proposed for these intrusions the name "plutonic plugs," without, however, defining very precisely the distinction between a plug and a laccolith. "They differ," he states, "from the laccolites described by G. K. Gilbert[4] in the fact that the molten rock did not spread out horizontally among the stratified beds so as to form "stone cisterns," although some of the hills named, which had not been examined by the writer, may reveal this structure when more thoroughly examined. * * * As they are composed of igneous matter forced into sedimentary strata and have a plug-like form, it will be convenient to call them *plutonic plugs*." Mato Teepee and Little Sundance Dome (Green Mountains) are cited as the two extreme types of plugs, the first an eroded remnant where "the arch of stratified rock which once surmounted the summit of the plutonic plug has been completely removed and the surrounding strata eroded away," the second "an unbroken dome of stratified rock arching over the summit of a concealed mass of plutonic rock."[5] Russell's view has been somewhat the subject of controversy. Pirsson[6] in commenting upon it believes "it is impossible to conceive that the tall, shaft-like mass of Mato Tepee, with a vertical columnar structure whose columns are several hundred feet long, can be a volcanic plug in a condition anywhere near approaching its original horizontal diameter. The mechanics of the jointing of igneous rocks forbids such a supposition, and we must believe that it represents only a still uneroded fragment whose vertical walls are produced by the columnar structure of a mass which formerly was of much greater lateral extension and possibly of laccolithic form."

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[1] Geology of the Black Hills of Dakota, by W. O. Crosby: Proc. Boston Soc. Nat. Hist., Vol. XXIII, 1888, pp. 488-517; Vol. XXIV, p. 11.

[2] Preliminary Report of the Dakota School of Mines, Rapid City, 1888, by F. R. Carpenter. Notes on the Geology of the Black Hills.

[3] Ibid., p. 50.

[4] Report on the Geology of the Henry Mountains, Washington, 1877.

[5] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour Geol., Vol. IV, 1896, p. 23.

[6] Geology and mineral resources of the Judith Mountains of Montana, by W. H. Weed and L. V. Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, p. 582.

IRVING.

A valuable paper by J. D. Irving[1] has recently been published, in which the conclusion is reached that the most important influence on the form of an intrusive body is the character of the sedimentary rocks invaded. With the following conclusions by Dr. Irving, the present writer is heartily in accord:

> In the Algonkian areas, where the schists and slates are tilted on end, the lines of least resistance lie in an approximately vertical direction, and we have a great profusion of dikes, conforming * * * to the strike and dip of the slates. So soon, however, as the eruptives reach the Cambrian formation * * * the lines of least resistance lie in a horizontal direction, and eruptives on encountering the heavier members of this formation have found it easier to insinuate themselves between the easily cleavable shales and sandstones than to break through the heavy overlying rocks. Therefore we find the predominant type of intrusion in the Cambrian formation to be the intruded sheet. * * * If the intruded mass has been large and the force of intrusion great, not only has the rock spread out between the sediments, but it has domed up those which overlay it, producing a laccolite.

Irving notes, further, that higher intrusions, doming up and breaking through the massive limestones of the Carboniferous, have "small thick-set" forms. He believes that Professor Russell "would have modified his views very much had he been able to see the eruptive region of Terry Peak."

It will be seen by the foregoing brief summary of what has been written on the younger igneous rocks of the Black Hills that there is some diversity of opinion concerning the form of the eruptive bodies and the dynamic conditions by which they originated. They have been variously described as volcanic and plutonic plugs, extrusions, sheets, overflows, laccolites, pustular eruptions, protrusions, and outbursts. One writer,[2] who visited only outlying subordinate laccoliths, remarked on the absence of dikes, finding no evidence as to "how the stratified beds below the domes that covered the plugs were displaced, *or perhaps fused*, so as to furnish room for the passage of the intruded material." In the mining districts, one continually hears mention of flows and overflows—the error arising from reverse conditions to those of the outlying districts—the region being characterized by dikes which bend into uncovered sills and by irregular cross-cutting lower contacts of laccolithic bodies. The natural inference from narrow and localized experience here is that these rhyolites welled up and overflowed an eroded surface, no cover being now visible.

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[1] A contribution to the geology of the northern Black Hills, by John Duer Irving: Ann. New York Acad. Sci., Vol. XII, No. 9, p. 187 et seq.

[2] I. C. Russell, loc. cit.

All the intrusions hitherto described and a number of others not recorded have been visited with a view to the preparation of this paper, and in this chapter the facts of observation are presented. As far as possible the theoretical conclusions deduced from these observations are reserved for a later chapter.

LACCOLITHIC INTRUSIVES OF DEADWOOD DISTRICT.

GEOLOGICAL MAP.

The accompanying geological map (Pl. XX) is of a portion of the Sturgis quadrangle (see Pl. XVIII) showing the Two Bit mining district in the region east of Deadwood and the intrusive masses northwest of the town of Runkel. These two districts are separated by a synclinal valley, the syncline being formed by the depression between the domical uplifts occasioned by the greater intrusions. Detailed study in these districts has thrown much light upon the dynamics of intrusion characteristic of the younger porphyries in the Black Hills, and it will be well to describe in some detail the laccoliths here as types from which may be drawn general conclusions that find confirmation in other localities.

The southern part of the map (Pl. XX) shows, in Two Bit Valley and on the hills east and west of it, a complication of intrusive sills and dikes in Cambrian dolomitic flagstones and shales, which can not be adequately represented on a map of this small scale. The most conspicuous feature in the field is the large number of sills, varying in thickness from 2 to 30 feet or more, and at a number of localities these are cut across by dikes, or themselves break upward obliquely across the strata, merging into other masses at higher horizons (Section D–E, Pl. XXI). In Two Bit Canyon good sections are exposed, but in the upper part of the valley the rounded hills covered with débris frequently show these alternations of porphyry and shale only by lines of surface float or in artificial diggings.

On the southwestern border of this map, and along Strawberry Creek on the extreme southern border, the Algonkian rocks are shown cut by numerous dikes, which pass up into the Cambrian series and form the conduits through which many of the higher sills and laccolithic masses were intruded. The base of the Cambrian, for a distance of about 5 miles south-southwest from Deadwood, forms a continuous escarpment, through which the porphyries have broken at many points, the quartzite dipping gently to the northeast, forming a wall along the crest of Strawberry Ridge, through which here and there a deep chasm marks the presence of a dike. On the northwestern dip slope of this ridge is usually found a cap of porphyry, frequently eroded away from the immediate summit of the escarpment, but leaving traces of its lower contact with the quartzite in the shape of irregular nodules of white quartz, which are characteristic of the contact zone where the porphyry sill and quartzite are seen together, as on the spur just south of Deadwood. At a higher point of the escarpment, near the head of West Strawberry Creek, there is some appearance of faulting, the Cambrian strata being broken across obliquely by the porphyry, and the basal beds of the Cambrian lying at a much lower level on the southwestern side of the valley than on the northeastern, where they appear to have been pushed up by the porphyry. In this case, as in others to be mentioned, the trend of the fault plane is NW.-SE., and the faulting appears to have been contemporaneous with the intrusion. This trend conforms with the general strike of the sediments here on the northeastern side of the Black Hills uplift. Mention has been made of the northeast dip shown by the quartzite. This dip is enhanced by the intrusives at many points; but far to the southeast, where intrusives are absent, a uniform dip toward the east is observed on the Algonkian slope, indicating that orogenic forces had produced the monoclinal structure as a whole, quite independently of the intrusive forces.

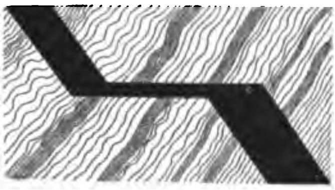


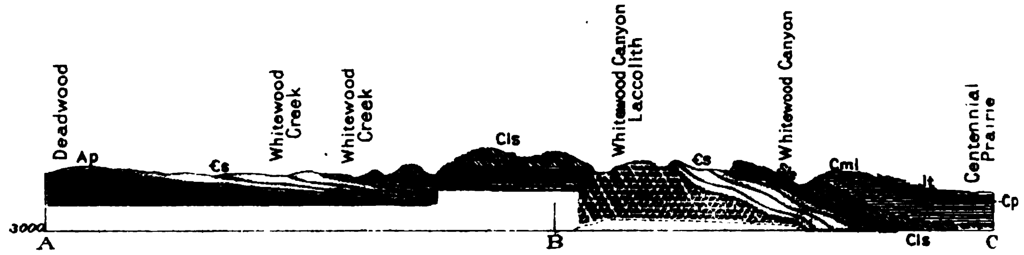
FIG. 68.—Crooked dike in schist, Deadwood.

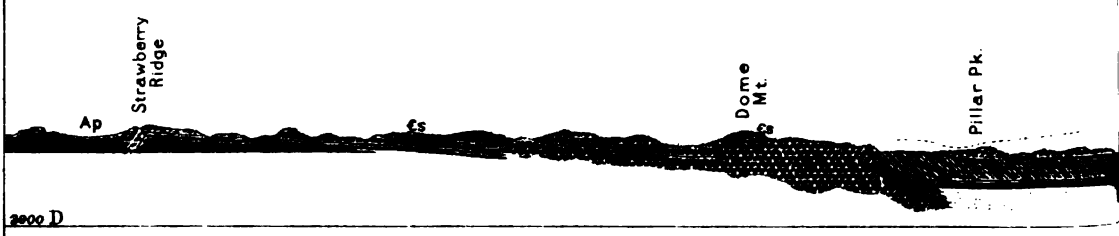
DIKES IN SCHIST.

In the wall of Algonkian schist opposite the Burlington station at Deadwood several small dikes, varying in thickness from 6 inches to 2 feet, follow very irregular fissures. In fig. 68 is shown one of these that illustrates the manner in which the rock gaped apart at the time of intrusion. It will be seen that the dike followed a crook or bend in a pair of matched joint surfaces, and had the movement of gaping been normal to the course of the joint as a whole the thickness of the dike would have been the same at the crook as elsewhere. Instead, the dike is thinner between the bends, showing that the rock moved apart to permit the injection (or was forced apart by it?) more readily in a horizontal than in a vertical direction. On the hill slopes east and southeast of Deadwood are shown good examples of the transition from the zone of dikes to that of sills in the Cambrian, and in these places there is considerable faulting on a small scale, which is one of the striking features of the mining district. In many places there is evidence of small dislocation in the Lower Cambrian beds, caused by movements of slipping on the laminæ or joints of the Algonkian schists beneath.

In a small open cut on the west side of Whitewood Creek, on the

U. S. GEOLOGICAL SURVEY





CRETACEOUS	JURATRIAS		CARBONIFEROU	
	JURASSIC	TRIASSIC	PERMIAN	
Kl	■	▨	■	▤
Lower Cretaceous sandstones and shales	Sandstones, limestones, and shales	Thick red marls and gypsum	Limestone over red sandstone (Minnekahta)	Minnelusa limestones and sandstone

STRUCTURE SECTIONS ON LI

By T. A. Jaggar

Horizo

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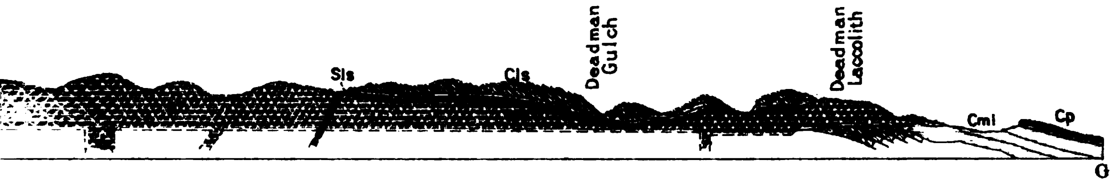
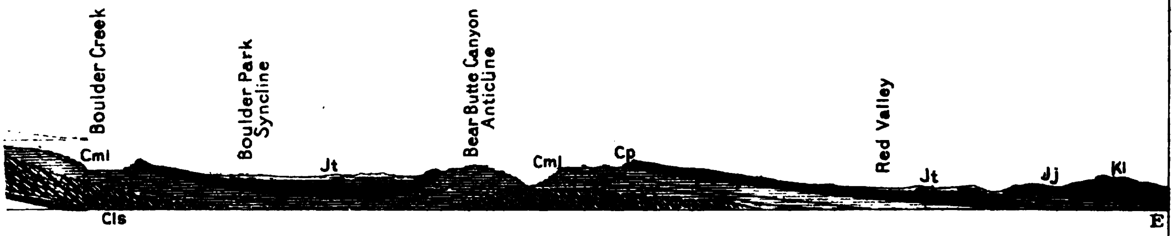




N D

	SILURIAN	CAMBRIAN	ALGONKIAN	IGNEOUS	
■	■	Cc	■	▨	▩
ray ie	Arenaceous spotted limestone	Shales, limestones, and sandstones	Phyllite, mica schist, quartzite, and amphibolite	Sills and dikes	Porphyry

-B-C, D-E, AND F-G, PLATE XX

ted by J. M. Boutwell

rtical scale

2 3 4 MILES

JULIUS BIEN & CO. LITH. N.Y.

spur just south of Deadwood, occurs the curious mixture of beds, due largely to faulting, shown in the accompanying diagram (fig. 69). A sill of porphyry some 5 feet thick, similar to others that are conspicuous in the cliffs above, caps the spur in the section exposed, and both over and under this are a few feet of glauconitic shaly beds of the Cambrian carrying *Obolus*. These dip northeasterly at a low angle, and rest directly upon the upturned edges of the Algonkian beds, which show some crumpling and confusion at the contact. This indicates that there has been movement directly along the base of the Cambrian, and the entire absence of quartzitic or pebbly layers, elsewhere characteristic of this horizon, indicates that this contact is not the normal unconformity. Such horizontal slipping parallel to the Cambrian contact is probably a result of movements of lateral extension in the schists when they were invaded by dikes, which necessarily forced apart and thickened the whole Algonkian series. On the western side of the outcrop, separated from the shales and the Algonkian alike by a "vertical"[1] (here a small upright fault plane), is a huge triangular mass of white quartz some 12 feet in diameter, apparently faulted into place as a solid block. In this case the slipping plane does not conform with the Algonkian laminæ, but intersects these on a transverse joint. There is no evidence in this place that the fault dislocated the porphyry above; the latter would seem rather to be younger than, or contemporaneous with, the movements in the rocks below.

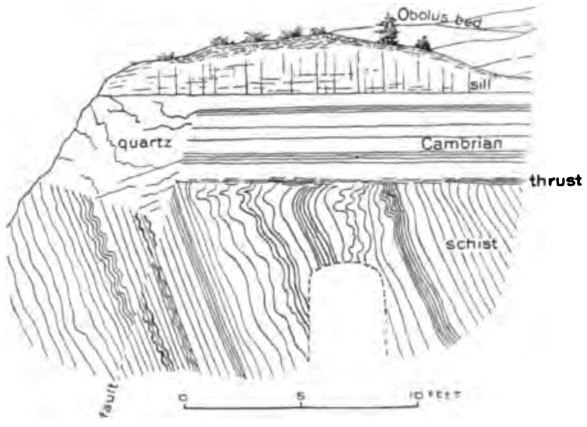


FIG. 69.—Outcrop showing faults, spur south of Deadwood.

Higher on this hill, to the eastward, other porphyry sills occur, and these sills may be differentiated megascopically by the occurrence or absence of large phenocrysts of quartz. In the lower sill these phenocrysts are absent, but in the sill next above they are visible. On following the hill along its south side, the lower sill, 5 feet thick at the point of the spur, was found thickening eastward, 20 or 30 feet of the fine-grained rock being exposed under the Obolus shale horizon. The beds here dip to the northeast, but show a tendency to curve downward to the northwest along the general strike over the porphyry. This lends additional confirmation to the supposed identity of this sill and the one first mentioned, and the evidence shows that in a distance of a few hundred feet a 30-foot sill thins to one whose maximum thickness is not greater than 6 feet. In such a case as this the inspection of a single outcrop would give but slight evidence of thinning; many cases studied indicate that such thinning in short distances is very common (cf. fig. 76). On the northern side of this spur the Obolus sandstone is found resting on the Algonkian schist, without any porphyry visible, presenting evidence that the sill has completely thinned out to the northward.

---

[1] A local mining term.

In an open cut opposite the Hoodoo shaft on Strawberry Creek a fault cutting Algonkian and porphyry alike is exposed (fig. 70). The northwest wall of the cut shows a triangular mass of porphyry bounded on one side by an oblique thrust plane that cuts across the schistosity. The latter here trends northwest and dips 50 to the southwest. A second lenticular tongue of porphyry is seen to thin out downward. The igneous contacts of both porphyry masses conform to the schistosity, and in this respect are like the greater number of dikes in the Algonkian. Similar contacts are exposed in the tunnel of the Dakota Maid, on the north side of Strawberry Gulch. These dikes are direct feeders of the large laccolithic mass of Union Hill, hence the 50° W. dip of their walls is significant (see Experiment IV, p. 298). The southern wall of this open cut shows two sets of joints in the schists, crossing each other, each making an angle of 60° with the horizon, one trending N.-S., the other S. 30° W. In the eastern end of the cut there is an upright lenticular mass of porphyry 18 feet thick in the middle and tapering rapidly, with northerly trend across the schistosity. These porphyries are of the older rhyolite series.

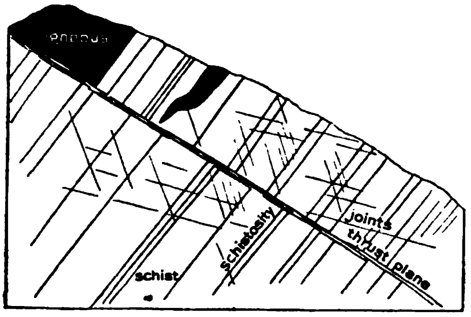
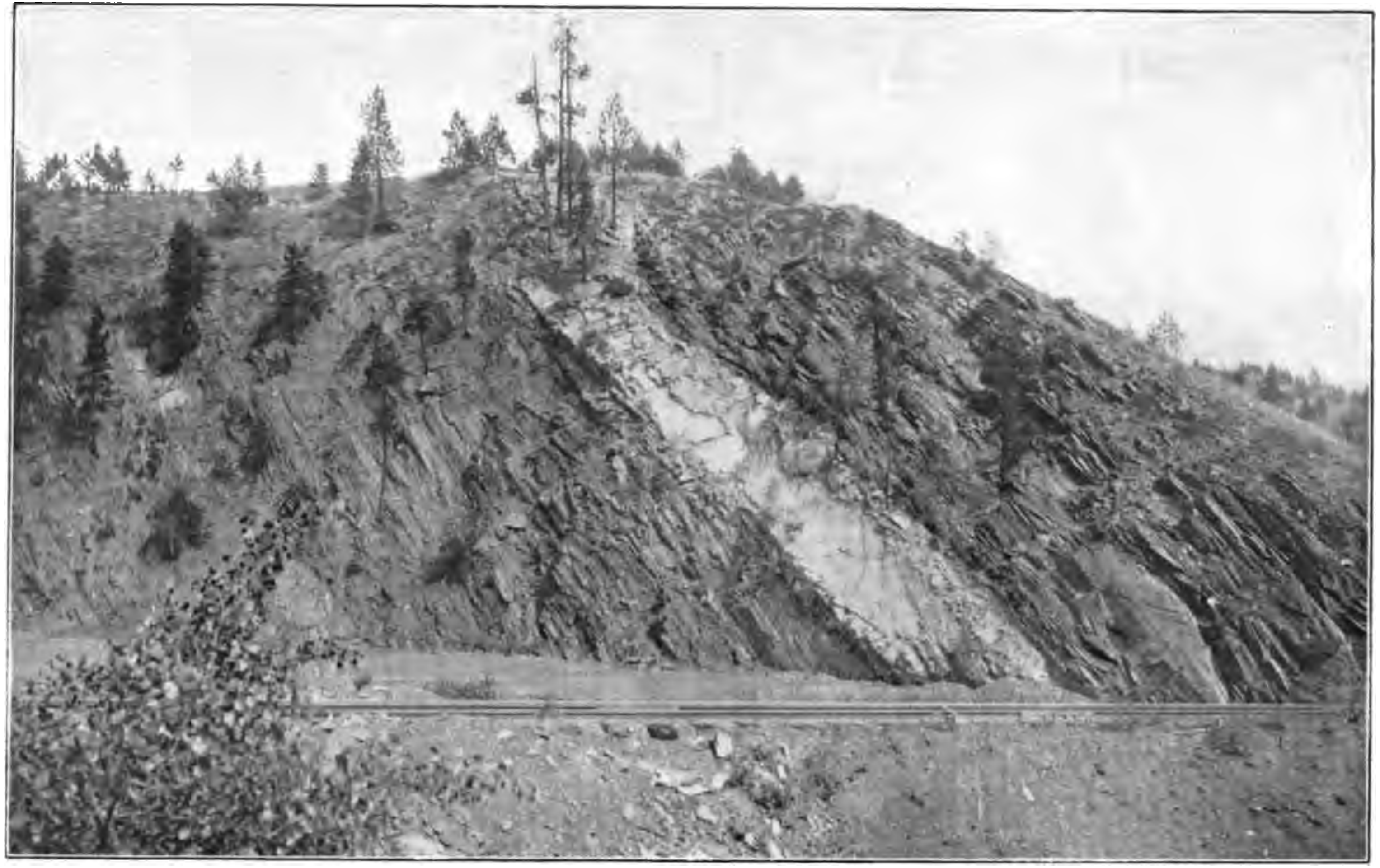


FIG. 70.—Faults and joints in schist, Strawberry Creek.

TRANSITION FROM DIKES TO SILLS.

The dikes filling fissures in the schist on planes of schistosity have in general a trend west of north, to correspond with the Algonkian strike. The inclination of the schistosity varies at angles between 45° and the vertical, being sometimes to the east and sometimes to the



RHYOLITE DIKE IN SCHIST, NEAR DEADWOOD.

west. Throughout the schist area west of Lead the Algonkian dip is westerly as a whole. Between Lead and Deadwood it is easterly, and a sharp fold, accompanied by fracture, is indicated by the change in dip about the region of the Homestake ore body. A dike in easterly dipping schist on the line of the Burlington Railroad near Deadwood is shown in Pl. XXII. This dike shows a slight tendency to develop short columns on the border, with a wide, massive medial portion. It will be readily understood that an igneous mass rising through an inclined fissure to the Cambrian unconformity would spread, on reaching the thin-bedded shales, in the direction of its inclination from the vertical. Some such inclination of the conduits upward and eastward, in the region east of Deadwood, where there is a recurrence of west-dipping schist (sections, Pl. XXI), accounts for the prevalent tendency of the porphyries to spread to the northeast (Experiment IV). In a railroad cut near the cemetery south of Lead, on the divide between Lead and Whitetail Gulch, is an exposure of reddish schist under

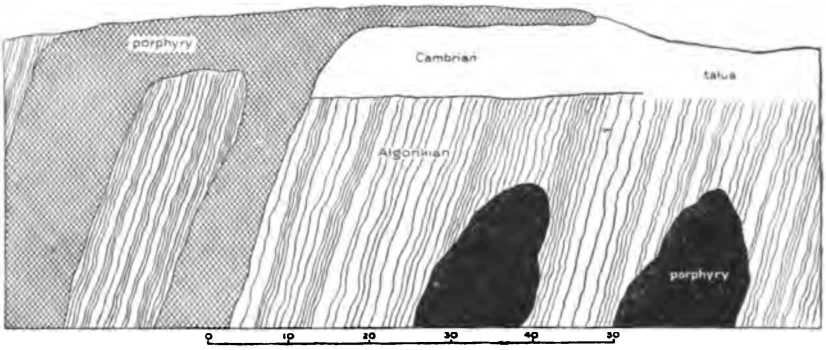


Fig. 71.—Section near cemetery, Lead.

Cambrian beds (fig. 71). Looking south in the cut, the dip of schist laminæ is seen to be eastward, and two dikes of fine-grained white rhyolite, in general parallel to the schistosity, pass up into the Cambrian, where they merge into a sheet extending to the west, the upper portion of which is eroded away. As shown in the figure, some faulting of the schist concomitant with intrusion is suggested by the progressive elevation of the upper schist surface eastward from the dikes. This may, however, be due simply to the lifting effect of the intrusions on the side of the hanging walls. On the east two dikes of dark green phonolite end in irregular bosses without reaching the Cambrian beds. These are lithologically identical with a sill and other dikes on the south side of the same hill (above Whitetail Gulch), and with the tabular columnar cap of the spur across Whitetail Gulch to the south. The rhyolite is the same as that which caps all the hills about the Homestake workings, and elsewhere on this same hill it is seen as a cap of some size. The structure is the same as that of the dikes in the Homestake open cut, where, looking north, they are seen to bend into sills which spread to the west (Pl. XXIII and fig. 72).

At the northwest end of Strawberry Ridge an interesting series of dikes passing directly from the Algonkian into the Cambrian is exposed. A 40-foot dike trending north cuts the quartzite obliquely across its strike. There is some slight suggestion of faulting locally in the quartzite on opposite sides of these dike fissures, but it is slight. The downthrow is to the north. Farther along to the northwest a break of 250 feet occurs in the quartzite ledge, occupied by a complex of dikes, and still others are seen beyond. In this case the composition of the rock varies, after the fashion of a composite dike; for a thickness of 75 feet on either side the rock is rhyolitic, while the middle 100 feet is coarser, showing large white feldspar laths.

A remarkable feature of the sandstone in contact with these dikes, also characteristic of the upper surface of the quartzite escarpment, is the occurrence of milky quartz in the form of infiltrations of irregular outline, sometimes filling cavities in the surface of the rock, but not in the form of veins.

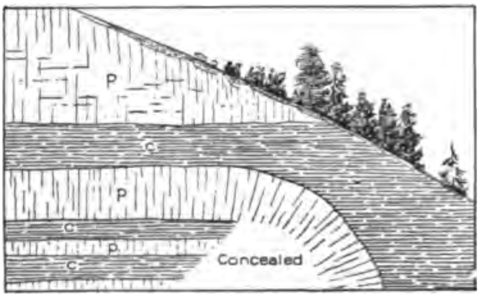
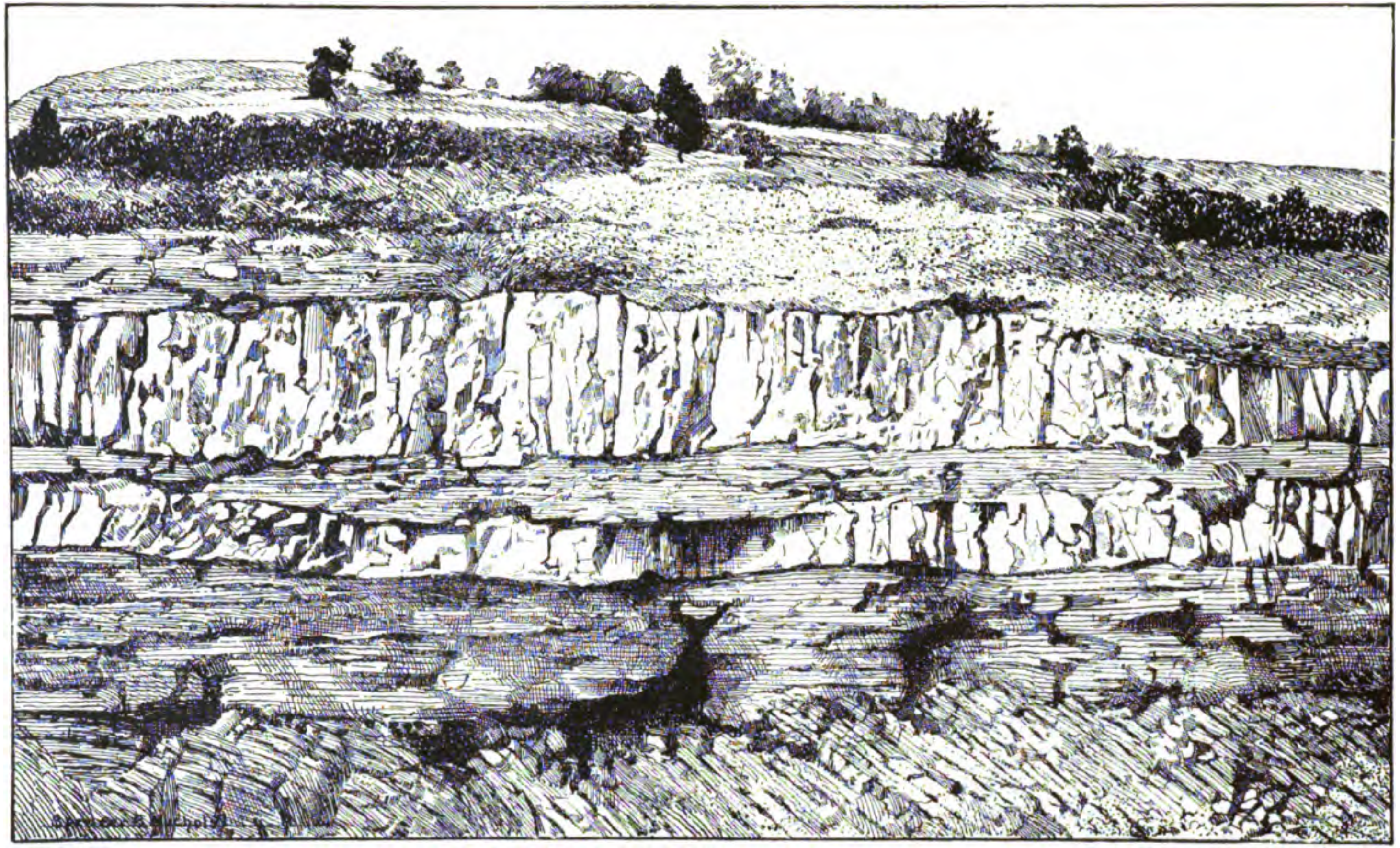


FIG. 72.—Dike curving into sill, Homestake open cut.

South of the main quartzite escarpment of Strawberry Ridge occurs a lower bench of massive white quartzite, forming cliffs 40 feet high capped by reddish shales which carry the usual white shell fragments (*Obolus*); above this, on the slope between the two quartzite outcrops, porphyry occurs. The thickness of the Cambrian quartzite would be so abnormally great were this porphyry a sill, that it seems probable it is a mass filling a strike fault fissure and that the upper quartzite bench is faulted up by the porphyry. This is the more probable, as the base of the Cambrian occurs at much lower levels across the valley on the south side of West Strawberry Creek. Under the lower bench of quartzite the mica-schist is found, and farther east an extremely complex structure of dikes and faults gives evidence that the conduit region at the time of intrusion was a zone of faulting and deformation, communicated from the schists to the hard beds at the base of the Cambrian. The schists here, as in the case described on page 201, contain large masses of white quartz. The hills a short distance west—i. e., farther within the Algonkian area—consist of slate capped with porphyry. The porphyry extends down the schist slopes in places and runs out into dikes in such fashion as to indicate that these seeming caps are in some cases stocks or conduits of irregular shape (Pl. XIX).



HOMESTAKE OPEN CUT, SILLS IN CAMBRIAN, SHOWING ALGONKIAN SCHIST BELOW.

SUMMARY OF DIKES IN SCHIST.

The exposed schist area southwest of Two Bit is a region of conduits which fed sills and laccoliths whose remnants still persist in the eroded monoclinal structure to the northeast. The dikes have northwesterly trend and east or west dip, with the schist lamination. Sills fed by such inclined dikes spread in the direction of the dikes' inclination from the vertical. Dikes in the Cambrian strata retain the northwesterly trend imparted to them by the schist below (Pl. XX). Deformation of the schist by faulting accompanied intrusion, and was transmitted to the Cambrian quartzite. Other faulting of later date intersects schist and rhyolite alike. Faulting on the plane of contact between Cambrian and Algonkian indicates movements of extension in the latter. The quartzite escarpment of Strawberry Ridge, representing the basal contact of Cambrian on schist, is faulted and broken through by many feeding dikes.

TWO BIT REGION OF SILLS AND LACCOLITHS.

WHITEWOOD GULCH.

The Two Bit sill district is limited on the southwest by the Strawberry Ridge escarpment, and this escarpment is practically continuous to the northwest as far as White Rock, above Deadwood. On the western slope of the ridge between Whitewood Creek and Spruce Gulch above Deadwood the complex of dikes and sheets begins. Fig. 73 shows diagramatically a section of the White Rock slope above Deadwood. The shales and sandstones of the Cambrian here dip 22° north-northeast, and a large dike of quartz-porphyry apparently feeds sills in the Cambrian flags and in the thick shale bed that lies immediately under the Silurian limestone at the base of White Rock. In the southernmost spur figured is shown a 3-foot dike of phonolite, which is younger than the quartz-porphyry that caps the ridge. The sill shows distinctly its intrusive character by the selvage at its upper contact, which is finer grained and of darker color than the rest of the mass. The upright contact, where the porphyry truncates the shale beds, shows in the igneous rock a lamination parallel to the contact.

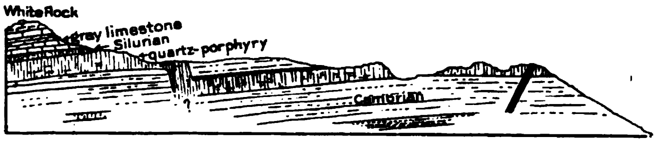


FIG. 73.—Section of east slope of Whitewood Gulch, Deadwood.

TWO BIT CANYON.

Fig. 74 shows the eastern wall of Two Bit Canyon formed by the northwest spur of Dome Mountain. This illustrates the transition from large, irregular laccolithic masses to fingering sills about their periphery, and is closely similar to the structure figured by Holmes in the Carriso and La Plata mountains (fig. 75). Two distinct varieties of eruptive are here present (fig. 74), and the lower hornblende-diorite-porphyry is probably the younger. The greater thickening of the laccolithic masses occurs at the base of the Silurian, where the porphyry in its upward progress met heavy resistant limestones, and the soft, thick shale bed at the top of the Cambrian offered an easier passage for spreading horizontally than was possible by continuing upward. Upward movement, or doming, eventually took place, when with continued inflow the mass and viscosity of the porphyry, as the result of lateral spread and cooling, were sufficient to flex

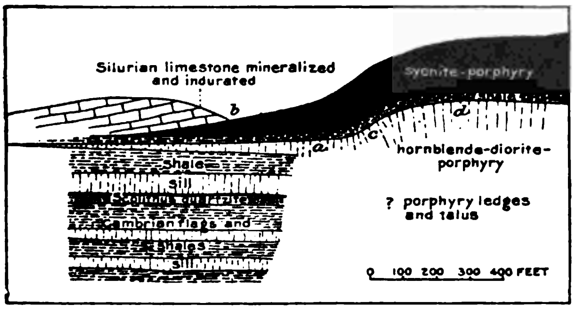

Silurian limestone mineralized and indurated
b
Syenite-porphyry
d
c
a
hornblende-diorite-porphyry
Shale
sill
Scolithus quartzite
Cambrian flags and
shales
sill
? porphyry ledges and talus
0 100 200 300 400 FEET

FIG. 74.—East wall of Two Bit Canyon.

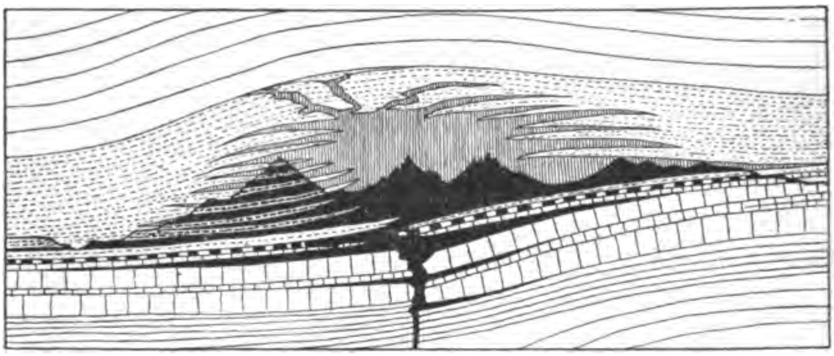


FIG. 75.—Section of La Plata Mountains (Holmes).

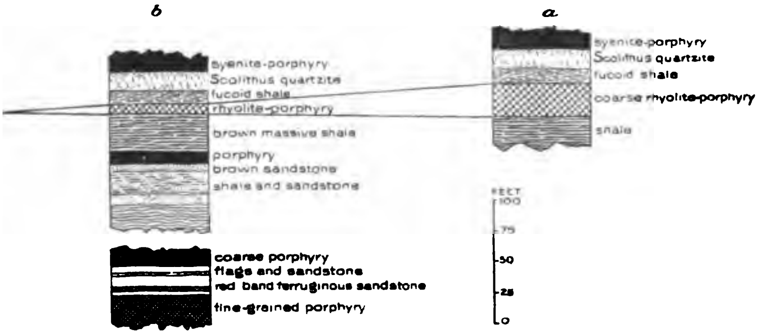


FIG. 76.—Sections showing thinning of Two Bit sills. *a*, Southeast side of Two Bit Canyon; *b*, Northwest side of Two Bit Canyon.

the thick limestones. In the figure the diorite-porphyry at the right is probably made up of a number of sills, though porphyry talus covers the whole hill slope, and if Cambrian beds occur there they are completely masked by the slide rock. In the uppermost bed, *a*, there are at least 250 feet of diorite-porphyry exposed, and apparently this mass lifted the syenite-porphyry above. That the upper laccolith ends rather abruptly to the northwest (Pl. XX) is proved by the fact that the walls of Two Bit Canyon opposite to the slope figured in the section (fig. 74) show none of the upper porphyry, and only one diorite-porphyry bench conforming to the bench in the figure. At the contact *b* the Silurian limestone is highly mineralized and silicified. At *c* the columns in the phonolite have a southerly inclination of 40°. At *d* they are nearly vertical. In each case, in other words, the columns are normal to the upper contact, and in a number of cases this variation in the inclination of columns was found to be a useful guide to the original curvature of a laccolithic mass where the covering strata had been eroded away.

The two columnar sections in fig. 76, constructed from outcrops in Two Bit Valley, illustrate the thickening of porphyry sills eastward across Two Bit Canyon, and show various members of the Cambrian, which may be used as horizon markers for identifying contiguous sills; *a* is from an outcrop on the east side of the valley; *b*, from one on the west.

In the Monarch shaft it is stated that the quartzite is faulted in steps, the ore occurring along the fault planes.

Cross-cutting sills.—The cases cited show that laccoliths under the great limestone thin out into sills, that sills thin rapidly (fig. 76), and that the region of sills is one where the alternation of shales and thin-bedded limestones through unusually thick series (Pl. XIX) affords innumerable splitting planes. The earlier rhyolitic porphyry in general spread through the Cambrian beds as sills, and the connection of one sill with the next at a higher horizon is usually an irregular dike or an oblique split corresponding to the more pronounced peripheral fractures about a laccolithic dome (Experiments III and IV; also p. 231). In a tunnel extending 375 feet eastward from the roadside in upper Two Bit Valley, Cambrian limestone flags and shales dip 6° N. 30° E. Three feet above the mouth of the tunnel a 6-foot sill occurs, and just within the tunnel is a very ragged dike (fig. 77). Some 50 paces within, a porphyry mass 40 feet thick, dipping 11° W., is seen to rise from the floor

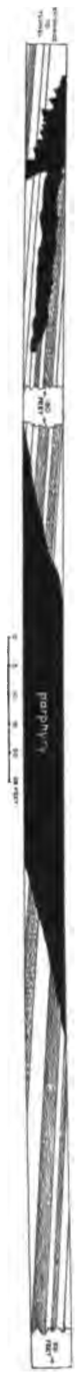


FIG. 77.—Section in tunnel east of Two Bit.

of the tunnel and cross the strata obliquely upward to the northeast. This may be taken as a type of the cross-cutting sill. The floor of the mass does not conform to the bedding, but is guided by it. The tendency of the porphyry to spread onward and resist the downward pull of dipping strata causes it to cut them transversely. This transverse cutting of beds is not confined to small sills. The rhyolite capping of the hill above the southern Terra open cut, probably a laccolith remnant, obliquely cuts across the Cambrian bedding only a few feet above the contact of the latter with the schists (Pl. XXIV). On the west side of Spearfish Canyon, high up on the summit of the limestone cliff below the mouth of Rubicon Gulch, a fine columnar sheet may be seen lying obliquely across the bedding of the limestone.

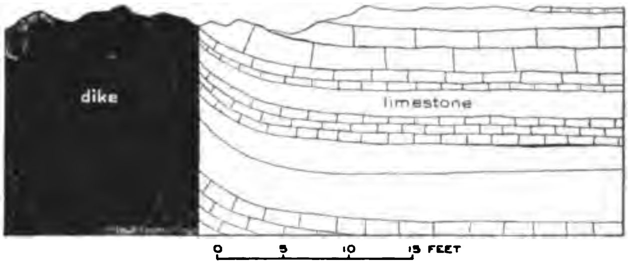


FIG. 78.—Dike crossing spur west of Peedee Gulch.

Dikes in Cambrian.—The later dikes probably found the Cambrian as a whole indurated by the earlier porphyry and rigid, hence more capable of breaking on smooth vertical joints. These dikes cross the country for miles in Two Bit, but are not very numerous. In fig. 78 is shown a dike 16 feet wide which cuts gray limestone on the hill west of Peedee Gulch. The massive limestone is bent up on the eastern side of the dike, showing that there was considerable upward thrust exerted by the magma after its first solidification on the wall. The dike trends N. 30° W., and hence is one of the numerous strike-fissure dikes which probably fed higher laccolithic bodies. If the magma which filled this fissure rose through west-dipping schists below, as usual, it is natural that it should tend to produce maximum deformation on the east.

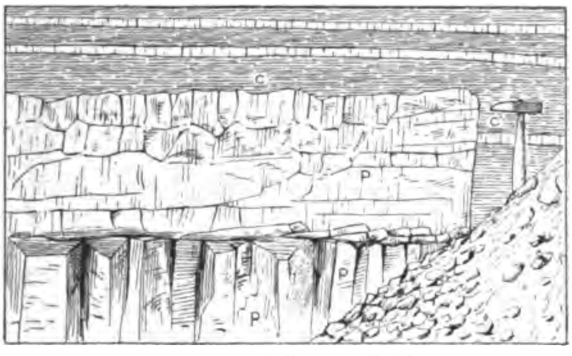
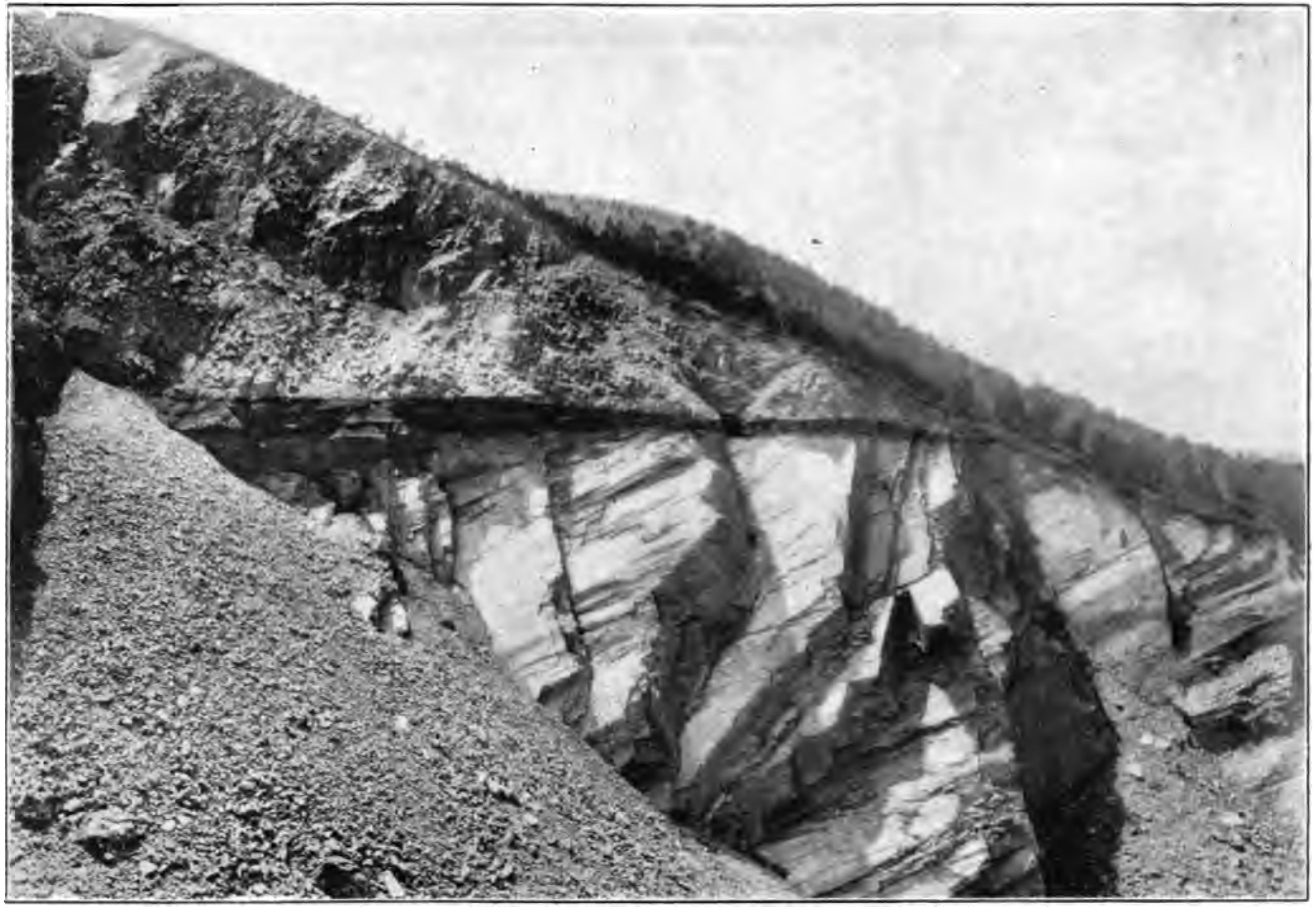


FIG. 79.—Abrupt termination of sill, east wall of Bear Butte Canyon, near Galena. The hammer rests on Cambrian beds.



SOUTHERN TERRA OPEN CUT, PORPHYRY ABOVE OBLIQUELY TRUNCATING CAMBRIAN BEDS, WITH SCHIST BELOW.

of the tunnel and cross the strata obliquely upward to the northeast. This may be taken as a type of the cross-cutting sill. The floor of the mass does not conform to the bedding, but is guided by it. The tendency of the porphyry to spread onward and resist the downward pull of dipping strata causes it to cut them transversely. This transverse cutting of beds is not confined to small sills. The rhyolite capping of the hill above the southern Terra open cut, probably a laccolith remnant, obliquely cuts across the Cambrian bedding only a few feet above the contact of the latter with the schists (Pl. XXIV). On the west side of Spearfish Canyon, high up on the summit of the limestone cliff below the mouth of Rubicon Gulch, a fine columnar sheet may be seen lying obliquely across the bedding of the limestone.

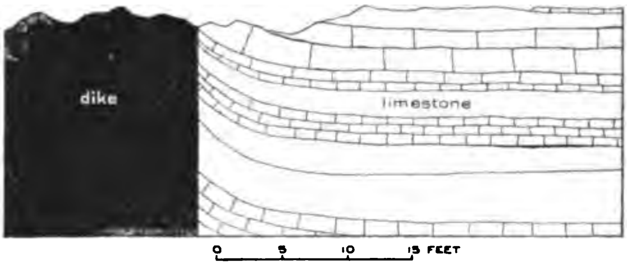


FIG. 78.—Dike crossing spur west of Peedee Gulch.

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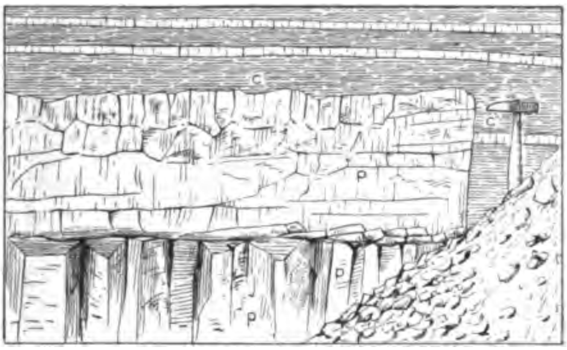
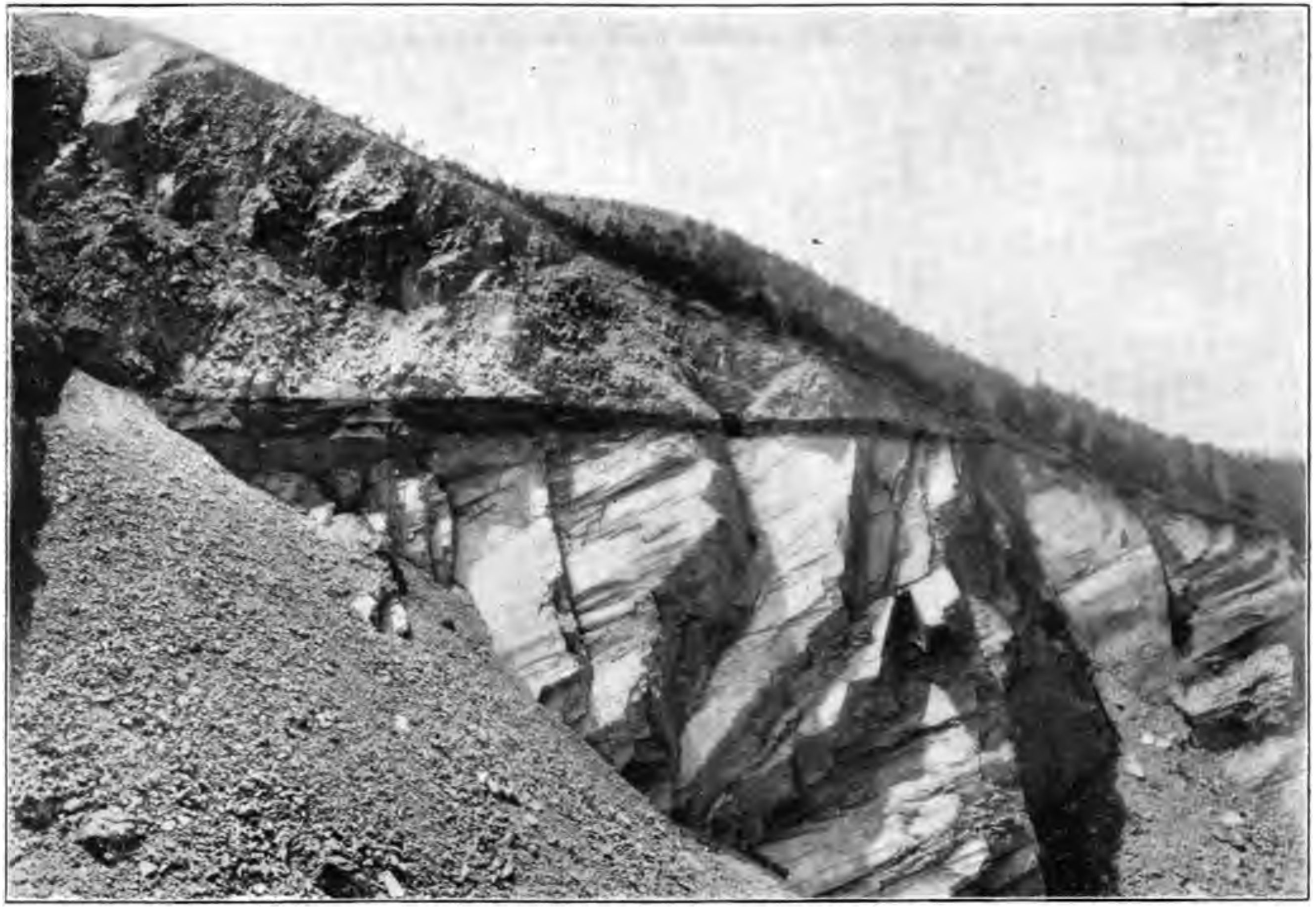


FIG. 79.—Abrupt termination of sill, east wall of Bear Butte Canyon, near Galena. The hammer rests on Cambrian beds.



SOUTHERN TERRA OPEN CUT, PORPHYRY ABOVE OBLIQUELY TRUNCATING CAMBRIAN BEDS, WITH SCHIST BELOW.

steeper northeast dips were encountered, the force of wedging apart horizontal rocks was converted into a thrust against upturned rocks. The result was more violent deformation of the initially dipping beds to form an unsymmetrical laccolith with steep northeasterly dip. In Chapter V it is shown by experiment that the fractures of a dome are radial on the crest, gaping upward and closed below; they are concentric on the periphery, gaping downward. These peripheral strike fractures open toward the porphyry core. If the dome is unsymmetrical, the rupture occurs first on the side of most intense flexure. In Dome Mountain, after the limit of flexure was reached on the northeast, the beds fractured and gaped open to admit the porphyry to higher horizons. In Lost Gulch, on the eastern flanks of Dome Mountain, the upper contact of this laccolithic mass with Silurian limestone is well shown. Here the limestone is seen dipping at an angle of 40°, so violently strained and contorted at its contact with the porphyry that it is infolded in a small pinched syncline plunging northeast between two lobes of the laccolith. A few hundred paces to the north the porphyry may be followed continuously, crossing Silurian, Carboniferous, and Minnelusa beds; here the flexure has passed into rupture. The phenomenon is the same as that represented by the cross-cutting sill in fig. 77, the only difference being that in this case large laccolithic masses are involved (Experiment IV, p. 298). A short distance farther northeast from Pillar Peak deformation of the sediments on a grand scale, probably due in part to the porphyries, may be seen in the canyon of Bear Butte Creek and in the synclinal basin of Boulder Park, this spoon being inclosed between three laccolithic uplifts of flexed strata (Pl. XXI, section D–E).

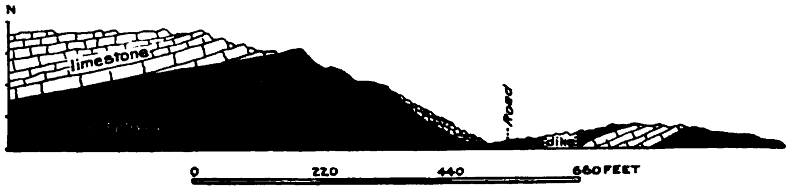


FIG. 80.—Section of divide, head of Lost Gulch.

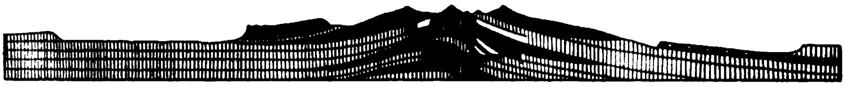


FIG. 81.—Section of Carriso Mountains (Holmes).

The southeastern border of the Dome Mountain mass shows less abrupt flank contacts, but is complicated with the conduits that fed the Bear Den Mountain laccolith. From the nature of the rock there is evidence that the later dikes were the feeders for Bear Den. In fig. 80 is shown a N.-S. section on the road which crosses the divide between Bear Butte Creek and Lost Gulch. In the cliff above the road on the north side shaly limestone overlies massive coarse columnar porphyry, the columns being perpendicular to the limestone contact. The limestone dips to the north and the upper surface of the porphyry shows some slickensides or rough grooving, which indicates movement parallel to bedding planes, of later date than the intrusion. Possibly such movement may be correlated with the intrusion of the later dikes. A conspicuous dike ridge crosses the saddle for a distance of one-quarter mile, trending variously from northeast to east. Above it to the north rises the talus slope of coarse porphyry, and similar float on either side of the trail of dike rock indicates that the larger igneous mass is cut by the dike. South of the dike occurs Silurian limestone over sills and Cambrian beds in the slope below to the south. The sequence here, then, is the usual one—sills in Cambrian, thicker lenses at the base of the limestone, columns normal to the cooling surface, and porphyry of two ages. As shown on the map, Pl. XX, this section immediately north of Galena is a complication of dikes and irregular bodies, marking fractures in the limestone through which the Bear Den laccolith was intruded. This mass breaks northeastward across the whole thickness of Carboniferous and Permian to the horizon of thick Red Beds, the wall of porphyry over Lost Gulch being underlain by a white bench of brecciated Minnekahta limestone.

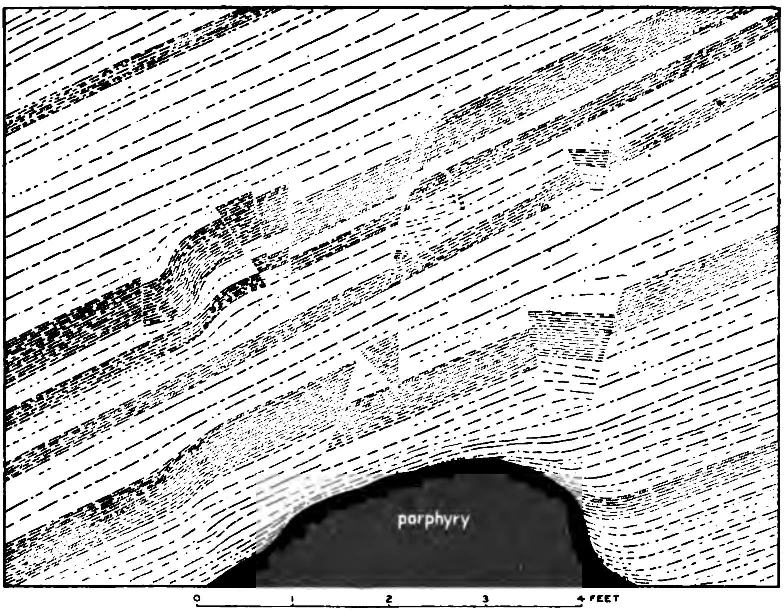


FIG. 82.—Section in shaft, summit of Dome Mountain.

On the summit of Dome Mountain, in several places, occur isolated Cambrian outcrops completely surrounded by porphyry. These appear to be large included bodies, mostly lying flat, carried up in the magma as a result of excessive doming. The arched strata, unable to stretch, fractured in many places, and the fractures filled with igneous matter; increased swelling separated the fractured pieces and erosion has revealed some of them. The same phenomenon is figured by Holmes in the Carriso Mountains (fig. 81). In a shaft 30 feet deep, through one of these masses on the summit of Dome Mountain, 24 feet of Cambrian shale is shown above, and 6 feet of porphyry in the bottom of the shaft. The porphyry surface curves downward to the south, showing dome shape, conformable at the top to the overlying shales, but breaking across them on the slope of the dome. The shales above are crumpled and their bedding is interrupted by very numerous small V-shaped faults (fig. 82). The shales dip to the northeast. Phenomena like this are abundant, and illustrate the way in which stresses due to intrusion are absorbed upward in incompetent strata.

SUMMARY OF TWO BIT REGION.

The Two Bit district contains a progressive series of intrusive types from southwest to northeast, this direction at the same time marking a progression from older to younger strata and a transition from approximate horizontality in the extreme southwest to pronounced dips and folds on the northeast. Dikes of trend mostly northerly, conformable to the lamination of the Algonkian, penetrate the base of the Cambrian, where a series of separation planes in thin-bedded limestones and shales offers the necessary conditions for the eruptive to spread horizontally in many thin sills. About the base of the massive limestones of the Middle Paleozoic, swelling en masse was easier than continued fracturing and horizontal splitting to form sills. At this horizon, where also a thick series of soft green shales under the great limestone offered easy material for crushing and opportunity for lateral extension, there followed a thickening of the uppermost sills into the irregular laccoliths of Dome Mountain and the adjacent masses which thin out across Two Bit Canyon to the northwest and across Bear Butte Canyon to the southeast.

The tendency to spread northeast is indicated by more violent deformation of sediments whose initial dips oppose extension in that direction, and by the igneous rock shown breaking across these sediments to produce at higher horizons the subordinate laccoliths of Pillar Peak and Bear Den Mountain. The whole series of eruptives of the Two Bit district may represent the peripheral intrusions of magmas that are most conspicuous in the more deeply eroded porphyry complex of Terry Peak (Pl. XIX). Evidence of strike faults in association with intrusion is well marked locally, the downthrow being on the southwest, the intrusive itself using the fault plane as a conduit and adding to the effect of dislocation by arching up and intruding into the strata on the northeast side of the fissure through which it came. Tyyes of these faults are seen at Strawberry Ridge and in the subordinate laccoliths of Deadman and Whitewood canyons (pp. 204, 217, 218).

VANOCKER LACCOLITH.

East of Bear Butte Creek (Pl. XX) is shown a large igneous mass occupying as a whole only the upper horizons invaded by the Two Bit series of intrusions. Separated from the latter by a synclinal valley, there is no evidence that the conduits which feed the Vanocker mass were immediately connected with those of the Two Bit district. Schists underlying the Cambrian escarpment south of Elk Creek show almost no dikes, and apparently the dip of the Paleozoic rocks is here the normal monocline of the Black Hills uplift. The lowest beds exposed in contact with porphyry in the Runkel district (see Pl. XIX) are the shales and sandstones of the Cambrian, and chiefly its upper members. These Cambrian beds cap the laccolith of Kirk Hill, which is separated by a synclinal sag on the southeast from a very large mass which extends northeast to Vanocker Creek and forms a great irregular range of hills composed almost exclusively of igneous rocks. Perhaps it would be better to call the whole mass a single great laccolithic intrusion with local irregularities of the upper surface. Here and there occur tabular cappings of stratified rock, the lower horizon, in contact with porphyry, being either the Silurian limestone or shales which are the uppermost beds of the Cambrian. If any trace of conduits is present it is in the immediate vicinity of the town of Runkel, where the gray limestone is irregularly fractured by the eruptive; and rising through an oblique fissure in the limestone a great dike is seen, inclined to the eastward on the hill slope north of the village. To the east a large sill follows a separation plane within the limestone series, which here has a thickness of from 600 to 700 feet, greatly in excess of the same formation north of the Two Bit region. The border of the laccolithic mass as a whole is marked by dips away from the hills of porphyry on all sides, and in this respect a southern extension of the intrusive from its conduit differs from the conditions observed in the Two Bit masses at the same horizon, where upper contacts on the southern side have in all cases been eroded away. This difference may be due in part to an easterly dip recurring in the Algonkian, and hence in the conduits, under the Vanocker laccolith.

Except where the Cambrian occurs on the southwest the upper contact in the Vanocker mass is with the base of the Silurian limestone, as in the case of Dome Mountain. At several points this limestone or the subjacent shales could not be identified at the contact, and apparently the intrusive had broken across and buried or else torn away this member, so that the contact appears to be directly with the gray limestone. On the north side of the Vanocker mass dikes varying in thickness from 30 to 80 feet cut both porphyry and sediments, and two big dikes may be seen upon the Fort Meade Reservation road northwest of Deadman Gulch. There is thus a tendency on this northern side to break across strata to higher horizons, and there is evidence of a younger porphyry which cuts the older and greater mass. The northern border of the Vanocker porphyry mass between Alkali Creek on the east and the eastern fork of Park Creek on the west, including the basin at the head of Deadman Gulch, is a different rock from the rest of the mass, being a fine-grained rhyolite, while the greater portion is a coarse syenite-porphyry. The contact between these two rocks follows roughly the divide at the head of Deadman Gulch and the northern slopes of the valleys of the two creeks mentioned, but a definite contact was nowhere found; possibly the finer-grained northeastern portion was more rapidly cooled against the sedimentary cover, and is a differentiated facies of the larger mass.

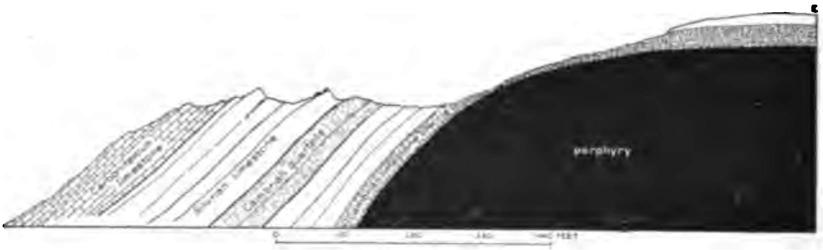


FIG. 83.—Section on west flank of Kirk Hill laccolith.

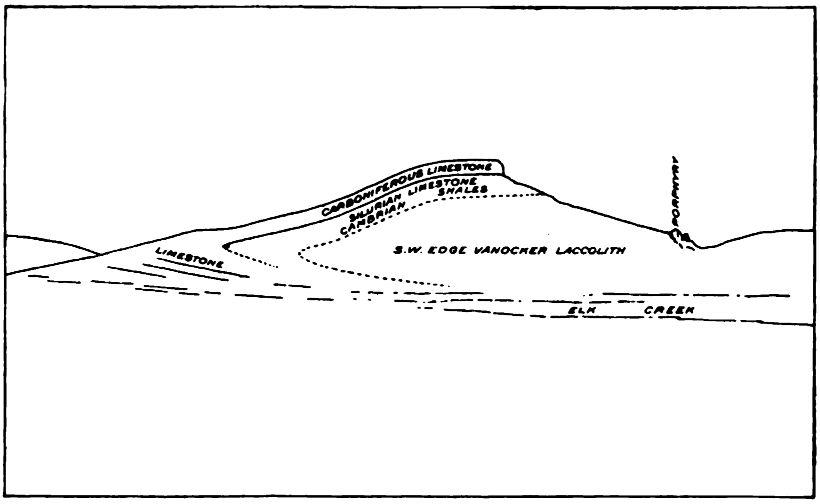
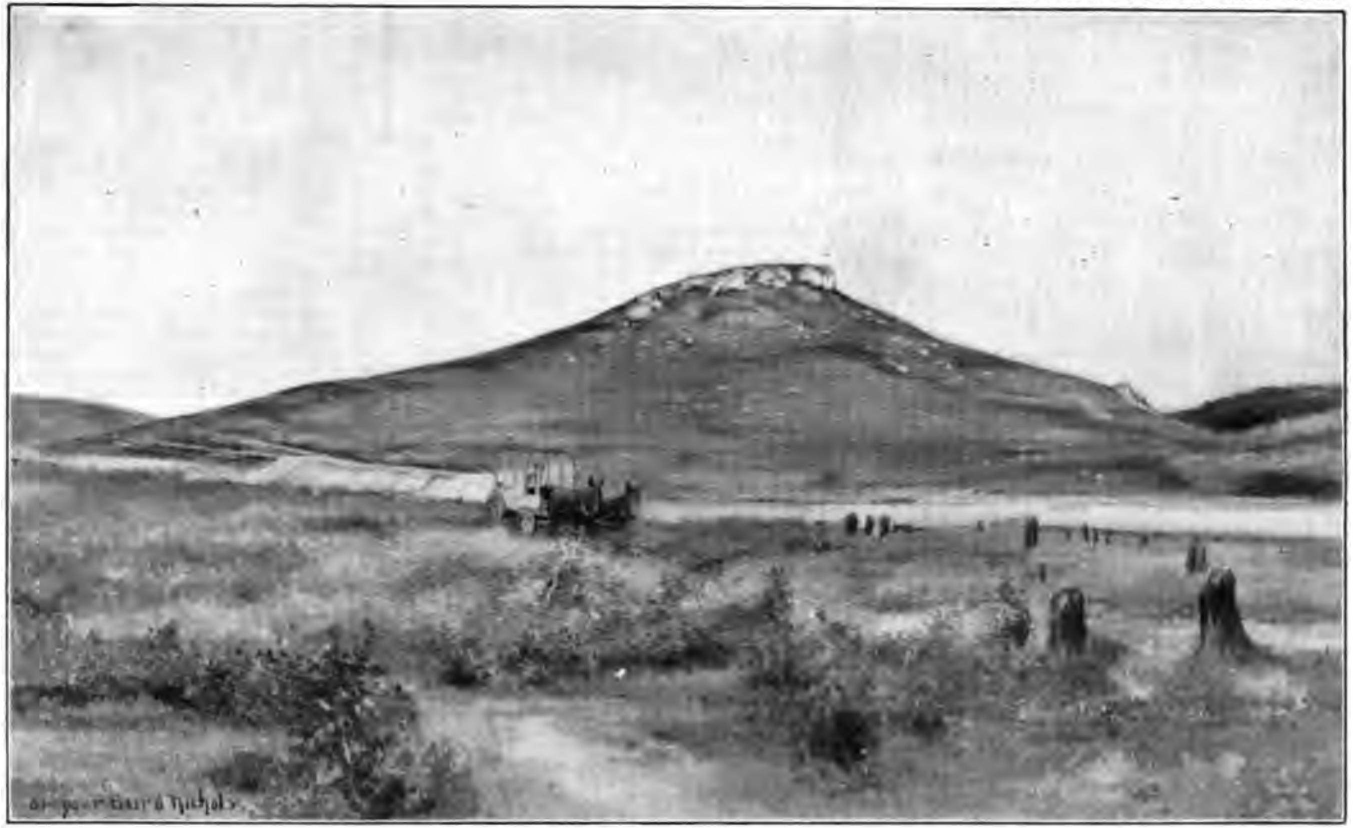


FIG. 84.—Southwest border of Vanocker laccolith, Elk Creek, showing surrounding rock formations.



SOUTHWEST BORDER OF VANOCKER LACCOLITH, ELK CREEK.

unsymmetrical laccolith mountain, Black Butte, in that erosion, by monoclinal shifting, has not progressed far enough to give the porphyry relief above the limestones which encompass it.

CROOK MOUNTAIN.

Crook Mountain, adjacent to the Whitewood laccolith on the northwest and separated from it by the synclinal valley of Sandy Creek, is the type of a laccolithic dome in which as yet the porphyry core has not been revealed by erosion. The Minnelusa sandstone and limestone dip away from the summit uniformly in all directions, and the purple Permian limestone is interrupted at only two points in its encircling escarpment. Through this escarpment the radial drainage cuts characteristic V-shaped gateways, the dips being steepest on the northeast side, where the Boulder Park syncline narrows to its region of maximum appression, confined between a plunging anticline on the east and the abrupt dome of Crook Mountain. On the northwest flank of the mountain Whitewood Creek has cut a deep canyon, revealing the underlying gray limestone, but not reaching the porphyry, which probably is intruded at the base of the Silurian. (Pl. XLI, II, geologic map of Crook Mountain.)

DEADMAN LACCOLITH.

The strata dipping to the north from the Vanocker laccolith form a syncline in Deadman Mountain (Pl. XXI, Section F-G), and in lower Deadman Gulch rhyolite again rises in a long, low dome which outcrops in the bottom of the deepest part of Deadman Canyon. At the point where this somber canyon opens on the north a cliff wall exposes the porphyry, filling a fault fissure which terminates this low dome on its northern side and permits the eruptive to break upward and outward to the northeast into the Minnelusa beds. There is thus exposed in cross section, for a distance of a mile, the upper laccolith, its conduit, and its source in the lower mass. On the western side a dike follows the fault fissure for a short distance along the contact between the faulted gray limestone and Minnelusa sandstone; in the bottom of the canyon the dike breaks across Silurian limestone and underlying shales. This dike fissure marks the fading out of one of the concentric fractures made by the lower dome in the limestones on its northern side, the middle portion of the fracture being occupied by the greater conduit. Four hundred feet higher, on the northeastern side of the canyon, the same Silurian limestone overlying the porphyry recurs, forced upward by the magma as it broke across the strata, while far below, on the northern side of the conduit, there are exposed, under the newer laccolith, beds of gray limestone that originally were continuous with those capping the uplifted mass shown on the same (eastern) side of the creek. (Pl. XXVI and fig. 85.)

A comparison of this Deadman laccolith with the one in Whitewood Canyon shows similar structure, the cross section revealed by erosion in this case making visible the conduit. This occurrence, and the dikes breaking through the upper Paleozoic strata a few miles to the southwest, show a repetition of the same phenomena that were observed in the cases of Bear Den Mountain, Pillar Peak, Whitewood Canyon, and Crook Mountain, where the greater eruptive masses show tendency to throw out offshoots northeast that mark the limits reached by intrusion in each district. The photograph of Deadman laccolith (Pl. XXVI) shows an abrupt break in the sky line occasioned by Bear Butte, another igneous intrusion far out in the plains, almost in the line drawn through Deadman laccolith from the greater interior porphyry mass of Custer Peak. Coincident with its greater remoteness from the seat of greatest igneous activity, the porphyry of Bear Butte has reached a higher horizon stratigraphically than that in contact with any of the other igneous masses of the northeast border of the Black Hills, and yet it shows the same structure.

The section from southwest to northeast, shown in Pl. XXI (F–G), is repeated in the sketch (fig. 85), but seen from the opposite side. Here is shown the eastern wall of Deadman Canyon, with the upraised limestones resting above the conduit and the laccolith extending to the northeast; the direction of its irruption seems to point toward distant Bear Butte as to another outbreak on the same line of igneous activity. Gray limestone occurs under the laccolith on the east side of the canyon, and a small remnant cap of limestone still rests upon the porphyry flank at one point.

Topographically in the Deadman as in the Whitewood laccolith, the limestones above the conduit region dominate the porphyry and occupy the highest summits. Intrusion at a higher horizon, however (Minnelusa instead of Cambrian), has permitted erosion to go deeper into the laccolith on the east and west flanks, and in consequence the basement strata and conduit are revealed. The flanking sediments, while still forming an encircling escarpment, do not lap over the edge of the lens of igneous rock, which has been eroded almost bare.

TILFORD LACCOLITH.

An eastern offshoot of the Vanocker porphyry mass occurs 2 miles west of Tilford. In structure this is an unsymmetrical laccolith, essentially like the one at Deadman Gulch, intruded in the Minnelusa shales and sandstones. From a road in the canyon west of Tilford the dome surface curving down to the east is seen to dip under a Minnelusa escarpment. Continuing westward, the road enters a narrow glen with vertical porphyry walls which show a remarkable massive platy parting. Finally the western contact of porphyry and limestone is seen, showing the limestone bed with gentle dip eastward, cut across by porphyry, which curves upward to the east and shows well-developed columns perpendicular to the contact. The limestone here seems but little deformed (Pl. XXVII). This again illustrates the invariable relation of subordinate laccolith to main mass, the conduit of the former being a peripheral strike fracture in the sedimentary cover of the larger igneous body.

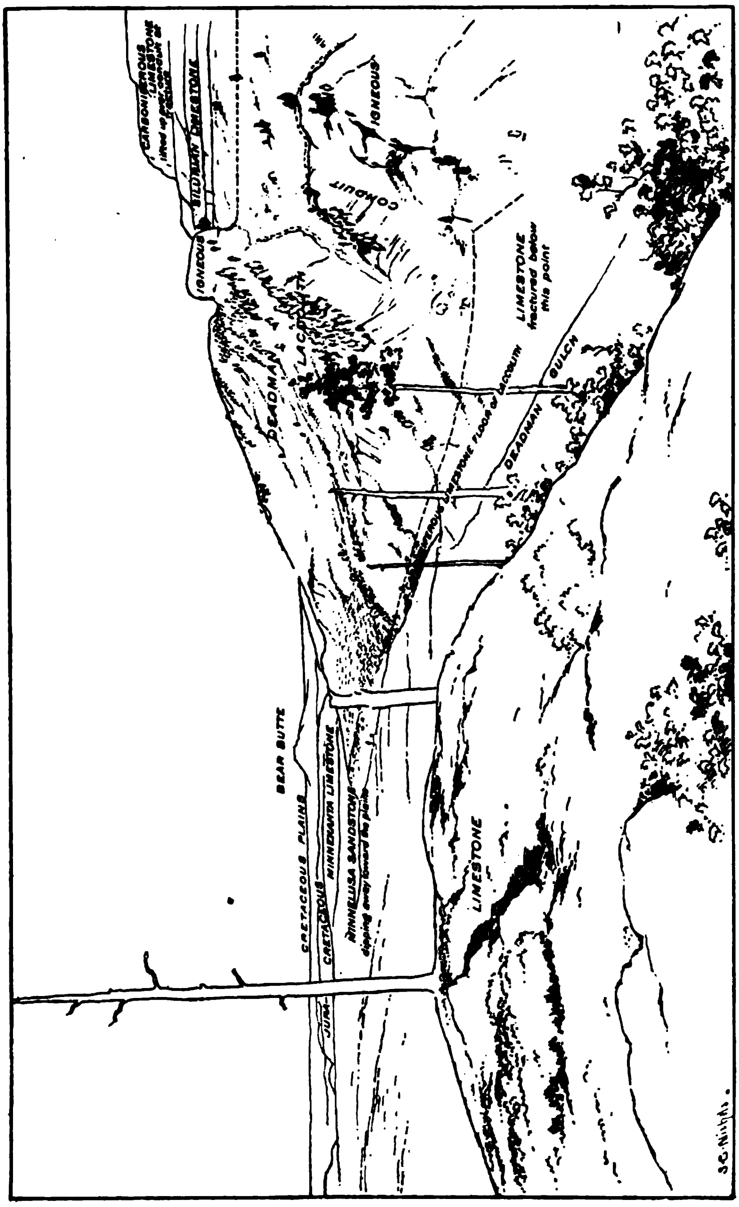
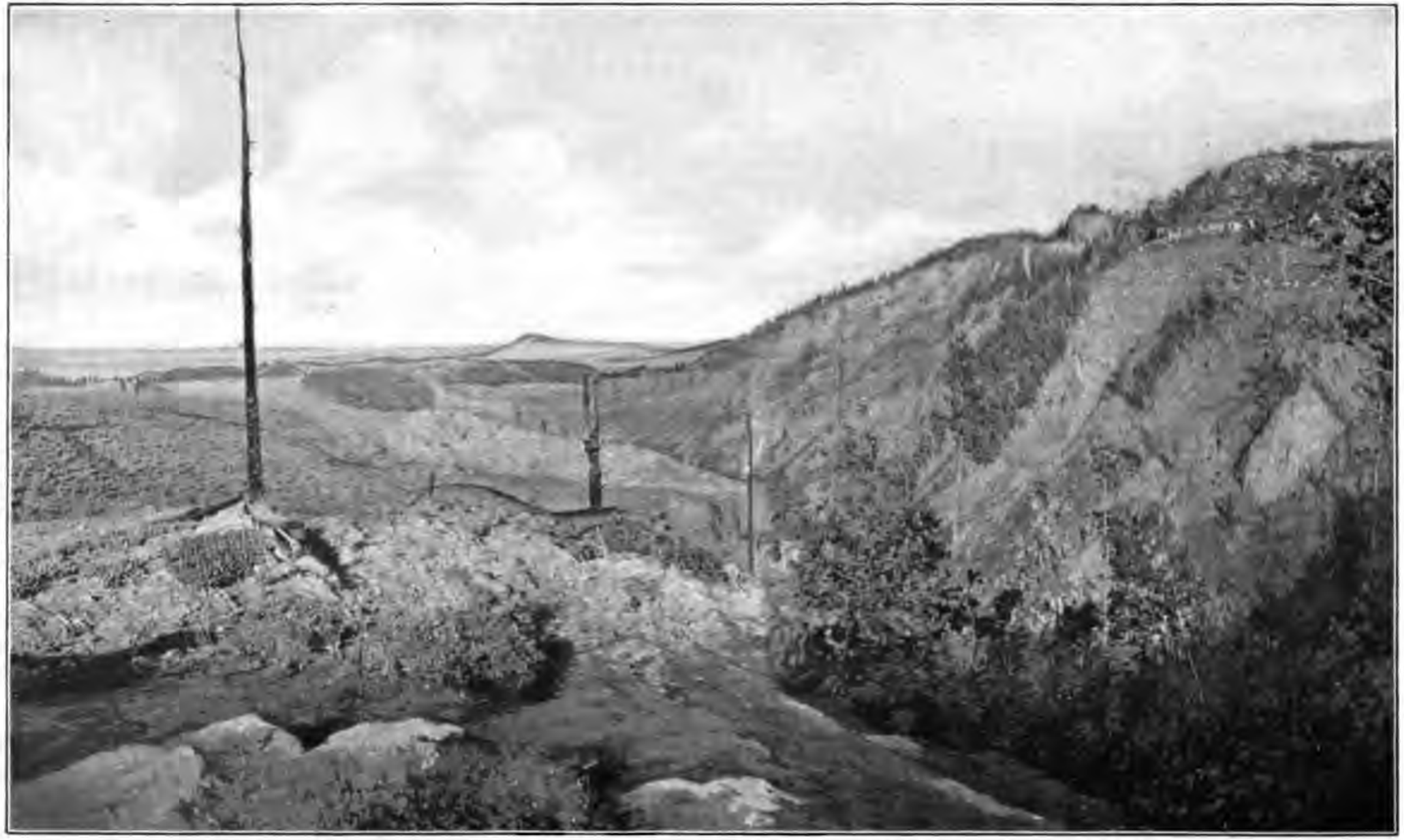

CARBONIFEROUS LIMESTONE lifted up over conduit or fracture
SILURIAN LIMESTONE
IGNEOUS
IGNEOUS
CONDUIT
DEADMAN LACCOLITH
BEAR BUTTE
CRETACEOUS PLAINS
JURA
CRETACEOUS
MINNEKAHTA LIMESTONE
MINNELUSA SANDSTONE dipping away toward the plains
LIMESTONE
LIMESTONE FLOOR OF LACCOLITH
DEADMAN GULCH
LIMESTONE fractured below this point
S.C. Nichols

FIG. 85.—Deadman laccolith, looking east across Deadman Gulch.



DEADMAN LACCOLITH, LOOKING EAST ACROSS DEADMAN GULCH.

a curve along its strike, and when viewed from a higher point at the western base of the mountain this curve is seen to continue in an elliptical wall inclosing an area which shows inner escarpments of similar trend that indicate a doming up of the strata immediately east-southeast of the mountain. The central portion of the inclosure thus encircled with curving dip scarps, Circus Flats, is a basin eroded out of the soft red beds, and the diameters of that portion of the swell which affects the beds now exposed are about 1½ miles east and west by 1 mile north and south (Pl. XXX). The inclosing escarpments are less clearly shown on the northwest, where erosion by Spring Creek and its tributaries has destroyed them. The encircling escarpments, however, northeast, east, south, and west, are sufficiently pronounced to leave no question that we have here a true quaquaversal, which differs from such domes as Elkhorn and Crook Mountain only by reason of the fact that erosion has not yet reached the resistant purple limestone and Minnelusa sandstone, but is still at work on the soft red beds, and accordingly produces a basin instead of a dome. The resemblance of this basin to a circus ring or race course is most remarkable, and on this account it has been named Circus Flats. Lying east-southeast of Bear Butte—that is, in a similar direction, relative to the greater mass, to that of the feeding reservoirs of Deadman or Whitewood laccolith—there is good reason for the assumption that this doming up of strata to the southeast indicates a subterranean laccolithic swelling that marks the first effort of the Bear Butte magma prior to the production of the fissure through which was forced upward the mass which now makes the mountain.

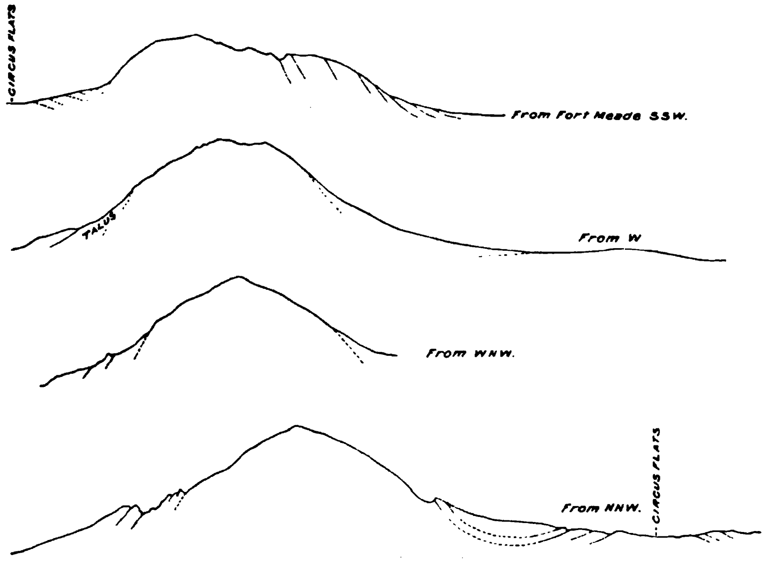
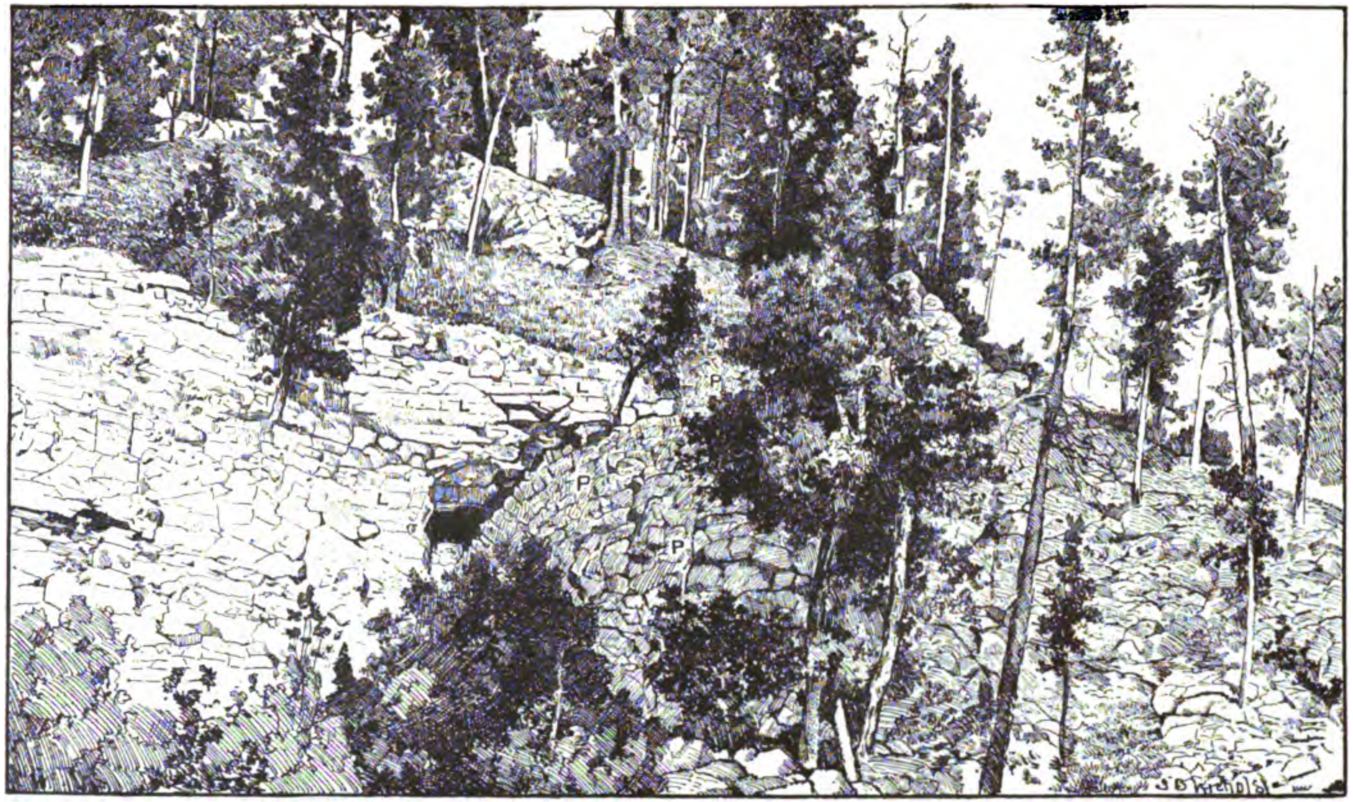


FIG. 86.—Profile sections of Bear Butte.



CONDUIT OF TILFORD LACCOLITH, SHOWING PORPHYRY (P) BREAKING ACROSS LIMESTONE (L).

The deformation of the sediments at the western base of the mountain indicates a sharp synclinal bend between the east-dipping members of the Circus Flat series and the beds upturned by the Bear Butte irruption. The section here exposed is shown in Pl. XXX. Immediately at the base of the mountain, dipping 60° to the westward, is a dense gray quartzite overlain by red and buff sandstones and white sandstone. Intercalated among these sandstone beds are sills of rhyolite 30 and 50 feet thick, representing that portion of the magma which breaks through the bends, as indicated in the original type sections in the Henry Mountains.

The topographic expression of this section is shown in the several profiles (fig. 86) and in the sketches (Pls. XXXI, XXXII). Especially striking is the drainage of Circus Flats, illustrating many features of stream capture, and the development of subsequent drainage, in a fashion that makes this locality a type and model for the study of physiography. The stream in the foreground (Pl. XXXII) is the master of the several radial streams that at one time flowed off the dome of Dakota sandstone. Outside of the Dakota rim these radial streams may still be seen, while Spring Creek circles around and avoids the dome on its western and northern sides. By reason of its advantage in fall, being the stream that enters Spring Creek at the lowest point, and the first to reach the soft Red Beds, the northward-flowing master radial stream has gradually reversed the drainage of the central portion of Circus Flats from radiation outward to radiation inward.

A comparison of the cross sections of Bear Butte with those of Whitewood Canyon, Deadman Gulch, and Pillar Peak (Pl. XXI) will show the writer's reason for reconstruction of the subterranean conduit on the western side of the butte. Erode away the section as figured (Pl. XXX) and remove the greater part of the eastern flanking sediments, and there will be left the Deadman laccolith section. There is some resemblance, too, to Black Butte in the Judith Mountains, but no surface indication of the subterranean feeding mass equivalent to the Circus Flats dome is there indicated. To this underground dome, which is probably much larger than the surface quaquaversal (see p. 268), Bear Butte is but a peripheral offshoot. In Oyster Mountain, north of Sturgis, there is a faint quaquaversal structure, and it is very probable that in the buried Cambrian beds between Deadman Gulch on the west and Bear Butte on the east there are large masses of igneous rock.

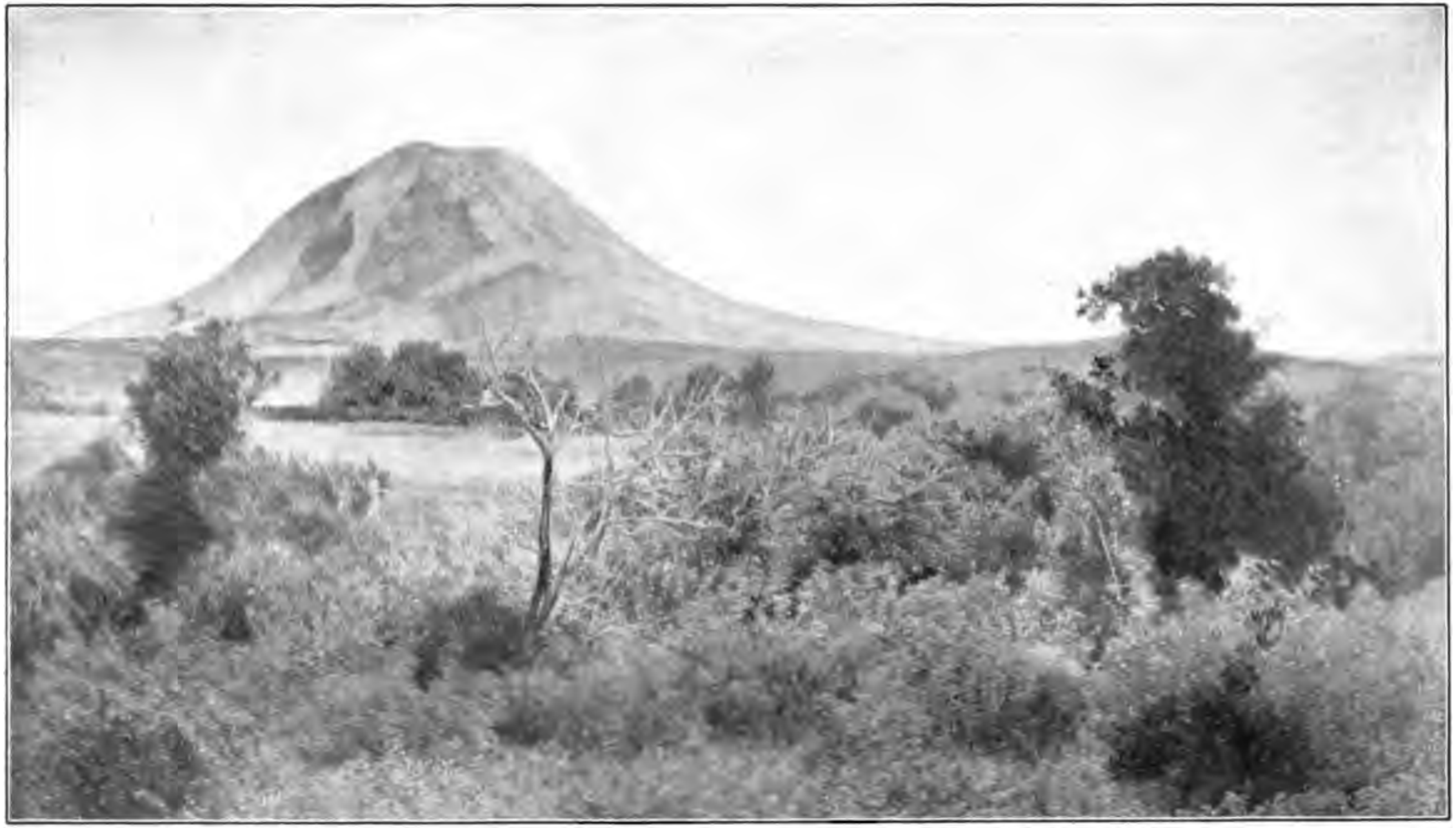
DEFORMATION DUE TO INTRUSION.

In the Whitewood Canyon intrusive body a cap of Cambrian sandstone still remains, and the flanking strata are shown in great completeness, the greater part of the porphyry dome being perhaps still masked by the mantling strata. In Crook Mountain, recognizable as laccolithic in character by its perfect dome structure, the porphyry is still unrevealed and the drainage radiates on the Minnelusa sandstone cover in all directions to supply the encircling greater streams which outline the periphery of the uplift. Finally, between those masses whose capping strata still persist, as between Crook Mountain and the Whitewood Canyon laccolith, synclinal depressions are observed, and to the east of the Pillar Peak, Bear Den Mountain, and Dome Mountain laccoliths, occurs a similar syncline, separating these from the Vanocker district. Inclosed by the whole group of intrusions is the Boulder Park Basin, which is bounded on the northeast by a great anticline that originated over the elongate intrusions that extend from lower Deadman Creek many miles to the southeast. The intrusives of this region, therefore, may be in part considered as sources of deformation with reference to the sediments, capable of exerting lateral as well as vertical pressure, and the strata yielded to the stresses applied by this agent in the same fashion and following the same laws of competent structure with reference to applied force that are observed in the greater plications of the Appalachians.

OROGENIC DEFORMATION.

It can not be asserted, however, that the Bear Butte Canyon anticline and the Boulder Park syncline were wholly induced by the intrusives. Similar folds occur along the eastern border of the Hills where porphyry is absent, as at Hot Springs, where the lower Mesozoic rocks are warped into massive folds of Appalachian type with axes following the general strike on the curve of the Black Hills ellipse. Such folds may be regarded as due to a settling back or overturning of the greater dome of the Hills, or to movements of actual extension, perhaps accompanied by fracture and faulting locally. Such greater movements gave passage to the eruptives; and the latter have been shown to produce great horizontal extension by filling the upturned Algonkian strata with dikes. This extensional movement, transferred to the flat Paleozoic sediments resting across the Algonkian beds, was transmitted horizontally by the competent Siluro-Carboniferous limestone, and was accommodated by folding.

Concomitantly the intrusive filled every weak place where the arches tended to open and where the incompetent Cambrian strata were thickest, avoiding the synclinal axial regions of appression; given impetus locally they wrinkled and ruptured the strata; in greater masses they transformed an initiated anticline into an irregular dome; they filled anticlinal elevations and accentuated the intervening synclines, buckling and warping the folds and destroying any original tendency to axial alignment. The Bear Butte Canyon anticline may be considered one of the original folds; it is distorted into the Vanocker-Deadman dome in its southeastern extremity, and it pitches northwest at Whitewood and flattens out. At Bear Butte Canyon it has the profile of a



BEAR BUTTE, FROM THE WEST.

step fold with its steeper limb toward the Algonkian region of conduits on the west—i. e., toward the applied force.[1]

The Boulder Park spoon is a remnant of the original syncline. At the southeastern end it doubles, forming the synclines of Deadman Mountain and Park Creek, both separating porphyry masses. At its northwestern end it is divided in two by Crook Mountain dome, which pinches it on the northeast side against the aforementioned anticline, and on the southwest side against the Whitewood Canyon laccolith. Beyond, to the northwest, the broad syncline continues, flattening out in the Jura-Cretaceous hills west of Whitewood, where it is again interrupted by Elkhorn dome. The next fold to the southwest was a great anticline over the whole Terry Peak district (Pl. XIX). Its crest is entirely eroded away; it was scalloped on its northern side into transverse folds of northerly and northeasterly pitch, with the anticlines domed up by the Spearfish Peak, Polo Peak, and Dome Mountain laccoliths. Along the synclines flowed the ancient Pleistocene streams (Pl. XX), and the history of the development from them of the present drainage forms one of the most interesting chapters in the evolution of the region.

SUMMARY OF SUBORDINATE LACCOLITHS.

The Whitewood Canyon laccolith was fed from a subterranean mass, which, in its first effort to dome the massive limestones, fractured them and arched them up north of the southern fault. Through a second fault gash the magma swelled to the northward and arched the Paleozoic beds into an unsymmetrical dome. Probably the fault died out upward, as it is seen to do laterally. In Crook Mountain the dome is preserved, with no conspicuous faults shown. In the Deadman laccolith the southern fault is replaced by a monoclinal fold; the representative of the northern one persists, and, since the magma was intruded at a higher horizon, erosion has removed most of the covering strata and revealed in cross section the conduit. Another stage is shown in the case of the Tilford laccolith, where the same kind of conduit section is revealed in part and the eastern upper flank contact is still preserved. All of these are unsymmetrical laccoliths, producing maximum deformation of sediments on the side remote from the Black Hills, and fed from inclined conduits.

Precisely the same structure is indicated by the evidence at Bear Butte, where the backward flexure of the limestone on the side remote from the Hills is still more intense, and the eastern subterranean dome indicates the direction from which the mass was fed. In all of these stages there are various sizes of laccoliths at the same horizon, and laccoliths of similar size at different horizons, though in no case can positive measurements be given, owing to the concealment in most cases of the extreme rim or wedge at the border. It may, however, be stated with some assurance that the ratio of breadth to height diminishes in the subordinate laccoliths, and that the higher the beds deformed by the porphyry the greater the steepness of the dome and the smaller the ground plan. All of these laccoliths are intruded among folds, through conduits which are in some cases demonstrably faults. Similar deformation occurring elsewhere, the preponderance of evidence shows that the intrusives were contemporaneous with or subsequent to orogenic deformation.

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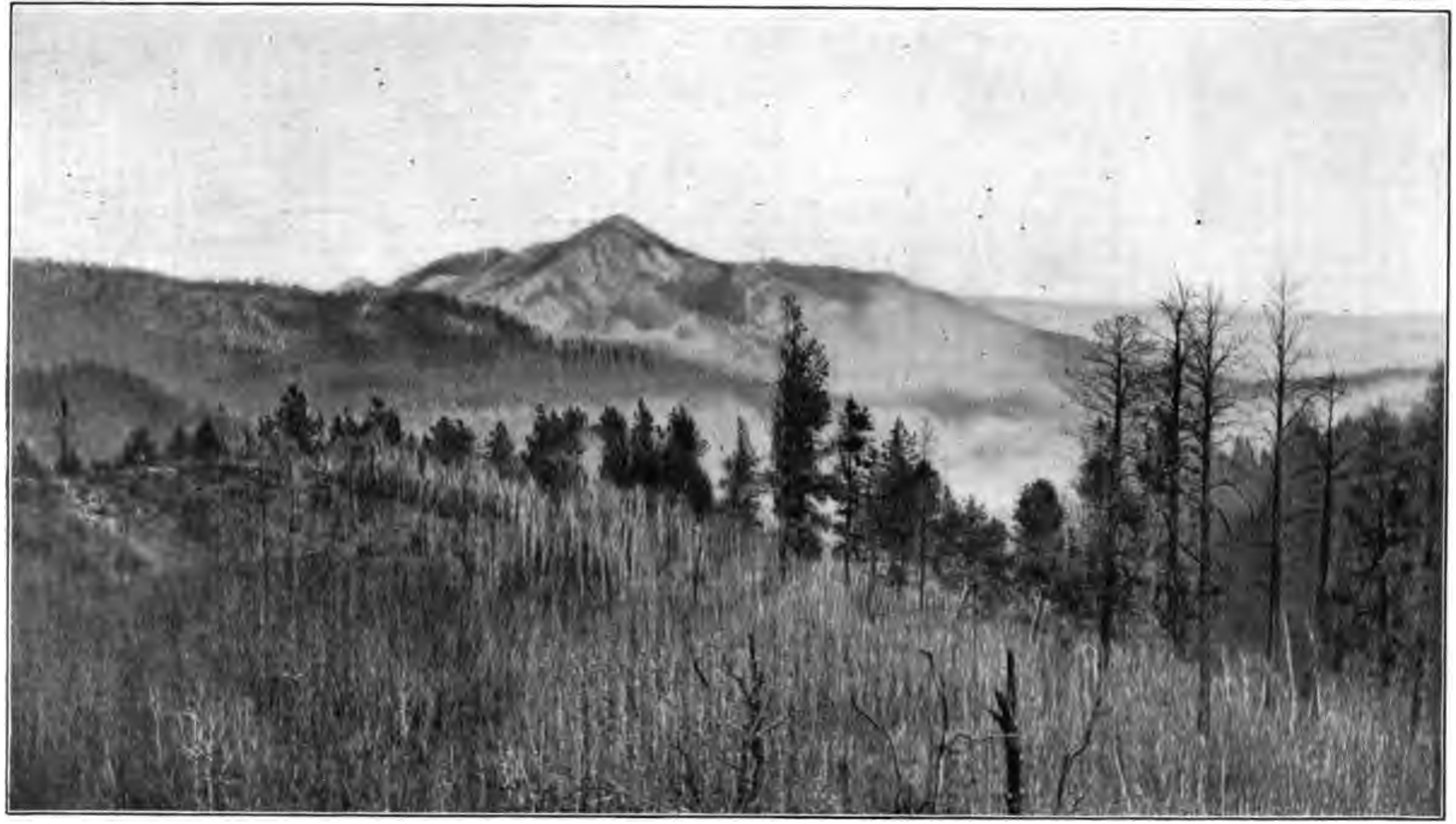
[1] Mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey.

LACCOLITHIC INTRUSIVES OF TERRY DISTRICT.

The several groups of intrusive bodies may be individually described under the name "complex." Five such complexes are distinct, and show evidence of being separated from one another by what were originally synclinal depressions in the covering strata. These are, from east to west, the Vanocker, Two Bit, Terry-Polo, Cement Ridge, and Bearlodge complexes. Of these the most conspicuous, by reason of its association with valuable ore in the most populous district of the northern hills, is the Terry-Polo complex.

The area of porphyries immediately associated with those which form the Deer Mountain Range, including Terry Peak, the highest point of the northern Black Hills, embraces about 80 square miles, naturally bounded by Spearfish Canyon on the west, that portion of the Red Valley known as Centennial Prairie on the north, and portions of Whitewood Canyon and Bear Butte Valley on the east, while to the southward Custer Peak forms the last porphyry remnant of importance in the schist region of maximum corrasion of the Black Hills dome (Pl. XIX). Genetically it is not improbable that Citadel Rock and Crow Peak, lying to the northwest, in the line connecting Custer Peak, the Woodville Hills, Terry Peak, and Ragged Top, may be related to this Terry group by reason of the fact that the greater number of known dikes in the Algonkian have a trend parallel to this one, and hence it is probable that great laccolithic bodies lying in a continuous line have a common conduit or group of conduits. Petrographically, however, they are composed of a variety of different rocks. The area of the Terry complex may be divided into three belts. The Deer Mountain belt includes Custer, Deer, Terry, Ragged Top, and Spearfish peaks, lying in general to the east of the exposed Algonkian. The second belt includes dikes and stocks in schist extending from False Bottom Creek southeastward to Bear Butte Creek. The third belt is made up of intrusives in dipping strata from Cambrian to Carboniferous, and includes the sills and laccoliths between Tetro and Whitewood creeks. The three belts are topographically distinct, the first being the edge of the great western limestone plateau, the second the Algonkian valley, and the third the Palæozoic escarpment, corresponding to the Two Bit and Vanocker districts southeast.



CROW PEAK, FROM THE SOUTHEAST.

STOCKS.

FALSE BOTTOM CONDUIT.

On the east side of False Bottom Creek, 1 mile above Garden, occurs a mass of phonolite of irregular form immediately in contact with schists. From this mass dikes run out to the southeast, and probably in other directions, though no actual junction has been observed. The mass as a whole forms a hill rising 400 feet above the creek, and the eastern and northern crests form a peculiar curved escarpment, made up apparently of coarse sheaflike joints or columns projecting obliquely upward and outward. In the bottom of False Bottom Creek, a few yards below the falls and immediately under this hill, the porphyry is seen in contact with schists, the contact being in general that of a dike parallel with the schistosity. There is no appearance of horizontal contacts with Cambrian beds in the hill slope. It seems probable that this is a true stock which represented the conduit of laccolithic bodies whose southern ends are now eroded away.

Exactly the same rock occurs in Cambrian strata on the spurs to the north, on both east and west sides of False Bottom Creek. These masses are dipping with the sediments, and form a series of lenticular bodies intruded in the northward-dipping Paleozoics on the several ridges between Spearfish and Miller creeks. On traversing any one of these ridges northward the edges of dipping strata and igneous lenses of varying composition form a series of steps or small transverse ridges, and the igneous bodies thus show signs of having formerly continued southward. Such southern continuation of the phonolite mentioned would pass over the False Bottom stock.

DEADWOOD CREEK CONDUIT.

A massive stock of diorite forms precipitous cliffs 1½ miles above Central, at a sharp bend in Deadwood Gulch, on the line of the Crown Hill branch of the Fremont Railway. This stock, as seen from the canyon, resembles more a huge dike, its contact walls being parallel with many other dikes exposed along this railroad between Central and Texana. The mass has, however, no considerable longitudinal extent, as it either forks into smaller dikes or thins out southward, and its northern continuation is obscure. This stock, as in the case of the False Bottom conduit, may be a feeder of laccolithic masses to the northeast, where, beginning along the eastern wall of Blacktail Gulch, a series of sills and laccoliths may be traced into the northeasterly dipping Paleozoic sediments; these form the Polo Peak group of hills, one of the most continuous and extensive porphyry masses in the region. In this is included the high porphyry hills between City Creek and Blacktail Gulch, and, farther north, the Miller Creek porphyry, Sheep Mountain, and Polo Peak. This is the region of greatest thinning in the Carboniferous limestone, and consequently the place where it was the most flexible to bend upward under pressure of porphyries below (see section on Pl. XIX.)

DIKES.

TEXANA DIKE DISTRICT.

The diorite stock, 1,500 feet thick, is only one of many conduits in Deadwood Gulch. West of it, along the railroad, there is an 1,800-foot section which shows chiefly porphyry dikes. Farther west two dikes, 630 and 10 feet thick respectively, cut the schist. In the spur south of Texana ten dikes are shown, ranging in thickness from 2 to 780 feet. Irving mentions twenty-two dikes from 10 to 100 feet in width between Texana and the great diorite mass. He states his belief that "were the whole of the Algonkian area carefully mapped, it is no exaggeration to say that at least one-third, if not more, would be igneous rock."[1] He refers to the diorite as a dike. The masses called stocks in this paper have usually an elongate trend parallel to the schistosity of the Algonkian, but their size and irregularity warrant separate mapping. The False Bottom and Deadwood Gulch stocks may occupy a common fissure, as they lie in a line parallel to most of the dikes. The dikes in Deadwood Gulch follow westward-dipping lamination planes and are very commonly associated with breccias on the walls, in zones from a few inches to a foot or more in thickness, made up of fragments of schist embedded in a muddy, siliceous, or carbonaceous matrix, the latter derived from graphitic schist. Sometimes the porphyry is charged with a jumble of fragments.

The most conspicuous of these dikes is the great Texana dike, locally 600 feet in thickness, which stands out on the wooded hill slope as a wall ledge, and may be seen as a prominent landmark from the high summits for miles around. This has been chosen as a type for naming a district which really involves all of the exposed Algonkian area east of Spearfish Canyon containing any porphyry. All of the railway sections in the Bald Mountain mining district show dikes and irregular intrusions of many shapes and sizes cutting the schist. Several of these are crossed by the branch railway in Gold Run Gulch, between Deadwood and Lead. A big dike forms the bottom of Whitewood Canyon just above Pluma and crops out on both sides of the canyon. This dike is so large and irregular as to be worthy of separate mapping as a stock (Pl. XIX). It is complicated with another crossing it at right angles, and apparently forks to the southward in the spur between West Strawberry Creek and Whitewood Creek. One of these forks may be seen in the elbow of Grizzly Gulch, the western branch of West Strawberry Creek. Another dike, readily observed

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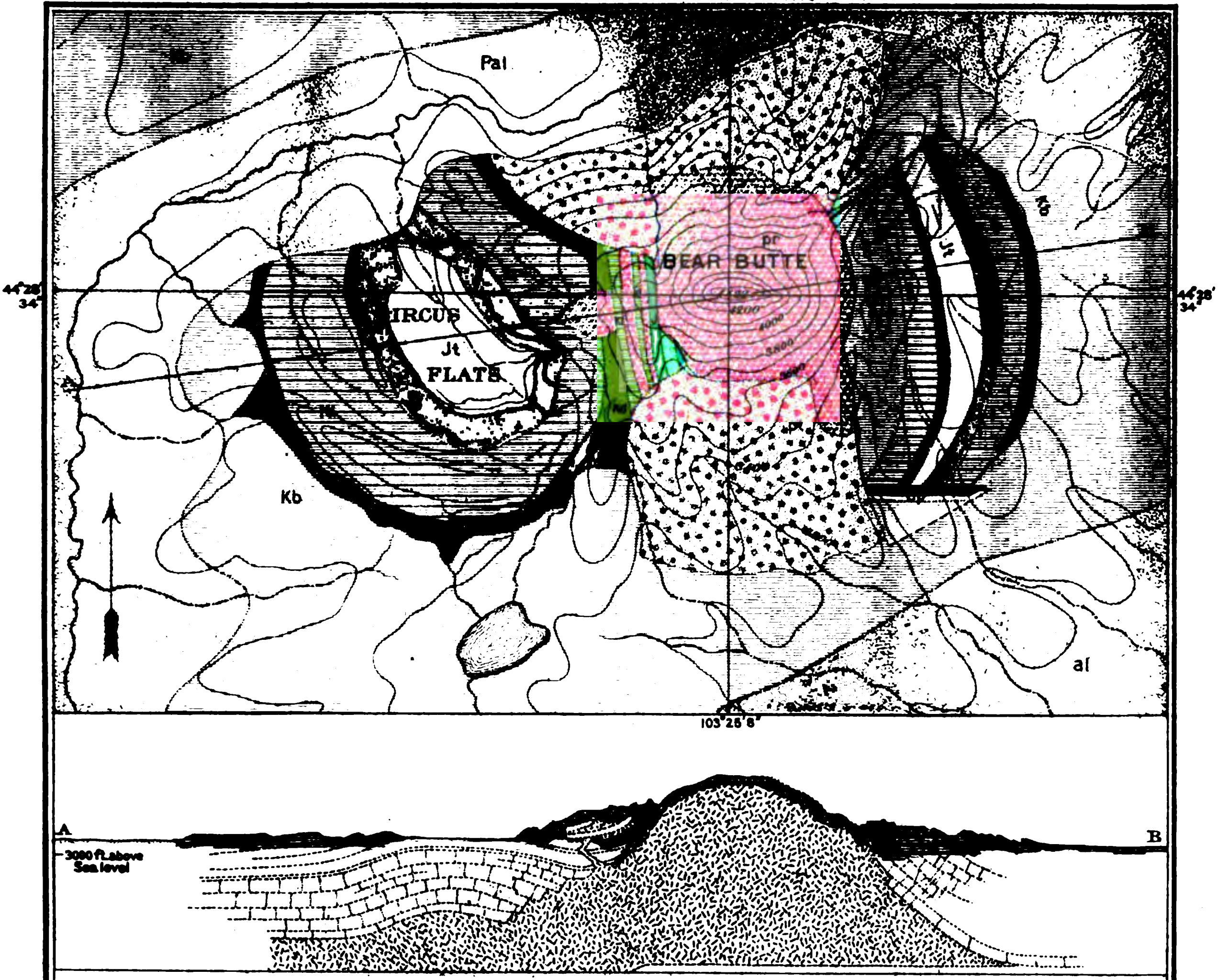
[1] Loc. cit. p. 209.



LEGEND

	CRETACEOUS			JURATRIAS		CARBONIFEROUS				
				JURASSIC	TRIASSIC	PERMIAN				
Pal	Kb	■	■	■	Jt	■	▨	Cls	▨	▨
Alluvial	Benton dark shales	Dakota brown sandstones	Lower Cretaceous sandstones, and shales	Sandstones limestones, and shales	Red marl and gypsum	Minnekahta "purple" limestone and lower red marl	Minnelusa sandy limestone	Gray limestone	Porphyry talus	Porphyry

Fault

Possible fault

Strike

Dip

GEOLOGICAL SKETCH MAP AND CROSS SECTION OF BEAR BUTTE AND CIRCUS FLATS

BLACK HILLS, SOUTH DAKOTA

BY T.A. JAGGAR JR.

1900

Horizontal and vertical scale

0 ½ 1 1½ 2 MILES

Contour interval 100 feet

Colored portions of section indicate rocks exposed

JULIUS BIEN & CO LITH N Y

on the line of the Burlington Railway, is seen across the creek near a sharp bend half a mile above Deadwood. This dike (Pl. XXII) is very uniform in width and parallel with the Algonkian bedding.

HOMESTAKE DIKES.

A section from southwest to northeast through the Homestake and Caledonia open cuts (fig. 87) serves to illustrate the frequency and thickness of dikes in the schist area that were conduits for westward-spreading sills and laccoliths. Here the schist dips to the east and contains much quartz, which in places is distinctly quartzite, elsewhere is massive quartz. The schist is red and ferruginous in this region, but talcose, slaty, or graphitic where less altered. The dikes average 35 to 40 feet in thickness. Three dikes in the Homestake section are associated with breccias; in one case on the foot wall; in another the fragments of schist are embedded in the igneous rock; and in the third case, a small 4-foot dike high up on the eastern slope of the main cut, a breccia 6 inches thick occurs on the hanging wall. These breccias sometimes contain fragments of both schist and porphyry, and therefore might be the product of faulting subsequent to intrusion. In other cases they are unquestionably the product of brecciation concomitant with intrusion.

COLUMNAR STRUCTURE.

Two interesting dikes are shown in Pl. XXXIII, occurring on the west side of Whitetail Gulch. These are of fine-grained white rhyolitic porphyry cutting graphitic schist. In both cases the portion next to the walls is columnar, and a zone in the middle is massive and irregularly jointed. This arrangement of massive medial portion and columnar borders, while not invariable, is very common. The explanation of the phenomenon bears on important questions of interpretation in the case of isolated erosion forms like Mato Teepee, whose origin has been the subject of controversy. It is commonly understood that columnar structure is the product of contraction in a solidifying mass, comparable to similar phenomena in drying starch or mud. Polygonal cracking of a dried clay surface is due to differential contraction, greater in the superficial sun-heated stratum than in the moister

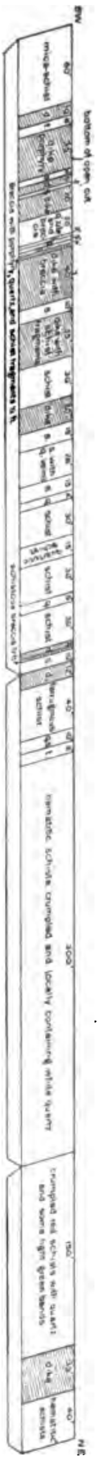
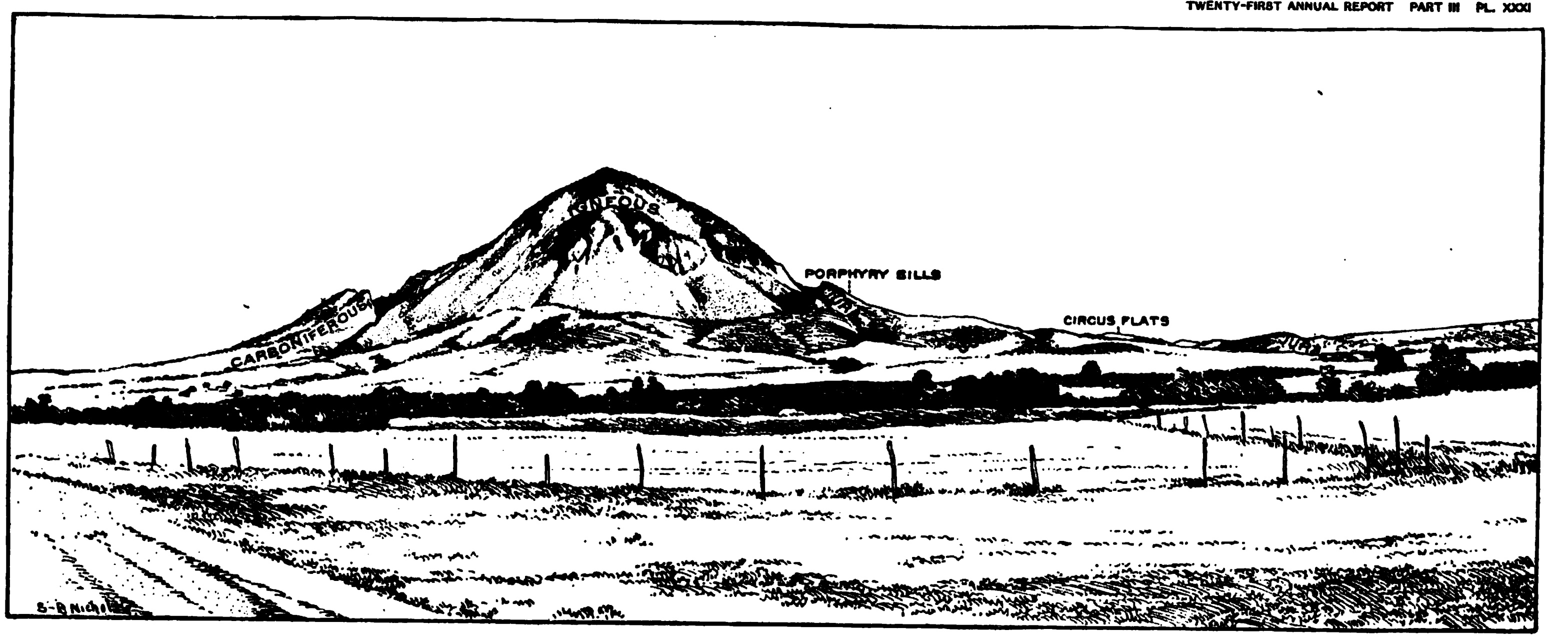


FIG. 87.—Section through Homestake surface workings. *s*, schist; *d*, dike; *t*, talus; *q*, quartz. Dip, 75° NE.; strike, N. 30° W. (both approximate). The sections probably overlap, making the error on the side of excess. Dikes do not always coincide with the lamination as shown, nor is the dip and strike uniform.

depths. The upper stratum, forced to diminish in area while attached below to a stratum retaining more nearly its original extent, cracks uniformly under the uniform tensions developed. Polygonal parting is the form that results from a sort of natural economy of plane fractures.

In the case of a fissure filled with molten lava the walls act as cooling surfaces, and the first solidification takes place in that portion of the viscous mass which is in contact with those walls. This initial congelation is very rapid, producing a glassy selvage of lower specific gravity and consequently less subject to contraction than the crystalline forms of the rock; from the border inward crystallization goes on thereafter more slowly. Contraction will show its effects, as in the case of mud cracks, only in those directions where linear shortening is impeded by attachment to a surface tending to maintain its original areal extent. Such a surface is furnished by the dike walls when firmly cemented to the magma by the selvage. In any direction parallel to the walls, contraction being impeded by the failure of the attached wall surface to shrink with the rest of the material, parting planes are developed as the magma solidifies, these planes naturally lying normal to the tension that acts parallel with the walls. Thus, polygonal bodies with faces at right angles to the dike walls are formed from the walls inward as solidification proceeds. If a loose, porous, muddy breccia forms the walls, offering no rigid surface of attachment for the siliceous glass, contraction will not be impeded by the surface of attachment and regular columns will not form.

The size of polygonal columns is in some way a function of the extent and thickness of the intrusive body as a whole. The thickness of a dike or a sill and the size of the conduit probably have some influence on the length of the columns, for in some cases these will continue across the body from wall to wall. In other cases they extend into the dike for a foot or more, and are there replaced by a massive middle portion. The dynamic significance of this massive medial zone is probably somewhat as follows: The columnar parting being dependent upon differential shrinking of crystallizing magma relative to glassy selvage, the tendency to produce parting normal to the walls becomes less in the interior portions of a dike. As actual shrinkage is equal in all directions, as soon as the rock has solidified to such a distance from the wall that the drag of the latter is less felt, those components which act crosswise, as well as the lengthwise ones, begin to take effect. The first result will be recorded by curvature in the inner prolongations of columns already formed. Farther inward, in the heart of the dike, the drag ceases to have any effect and contraction takes place equally in all directions, producing irregular joints. If in this last stage fluid magma is still present in the region of the conduit or the depths, contraction may be compensated by movements in this magma, so that no parting is required. Good columns are seen



BEAR BUTTE, FROM THE NORTH.

at the head of the northern open cut at Terra, in the great headland capped by a laccolithic mass which projects from Dome Mountain into Two Bit Valley, in the Needles, and in Mato Teepee, hereafter to be described.

FEEDING DIKES.

The dikes of the Homestake open cut illustrate the great profusion of porphyry-filled crevices in the Algonkian (fig. 87). An interesting feature of the upper portion of the main open cut at Lead is the curvature of these dikes into sills in the Cambrian (fig. 72). A dike in the Caledonia open cut illustrates the formation of small columns on the walls. The occurrence of so many dikes and stocks in the small area of Algonkian schists exposed by erosion gives ample evidence of the mode of intrusion by which the porphyry reached the base of the Paleozoic series. There is, obviously, an equal number of dikes under any of the greater laccolithic masses, just as there is here ample evidence from the porphyry hill caps that laccolithic masses once extended over the area now occupied by dikes. There is no reason for supposing that independent laccolithic masses have single shaftlike conduits or "necks."

SILLS.

Sills occur in False Bottom Creek below Garden, in Squaw Creek, and in Annie Creek, showing phenomena similar in all respects to those of Two Bit Valley (p. 207). In the case of the sill conspicuous under the cliff north of Garden, truncation of Cambrian beds from southwest to northeast is shown at a very oblique angle, so that it is only by very close inspection that the departure of the plane of intrusion from that of bedding may be detected. Similar oblique truncation of bedding is shown in Squaw Creek, where the porphyry lenses reach a thickness of 50 feet in places, more than the height of spruce trees growing on a Cambrian bench below. These are in part the western extension of thicker porphyry masses at the head of Squaw Creek.

COMBINATION OF SILLS AND LACCOLITHS.

The porphyries in the schist area, representing laccolithic remnants, form domelike mountains which at first sight give the impression that the topographic domes are structural ones. Bald Mountain and Sheep Mountain are types of this, the dome shape being due to uniformly graded slopes on a hill made up of approximately horizontal sills and Cambrian strata, with a thicker remnant cap of porphyry forming a rounded talus of coarse blocks ("Felsenmeer") upon the summit. In Pl. XXXV, looking southwest from Polo Mountain toward Terry Peak, the schist area is seen to be an old lowland, Sheep Mountain on the left and Polo Peak in the foreground representing the base of the northern sedimentary rim of the Black Hills, thickened by porphyry. The straight divide seen in the middle distance is a mass of Tertiary and Pleistocene deposits.

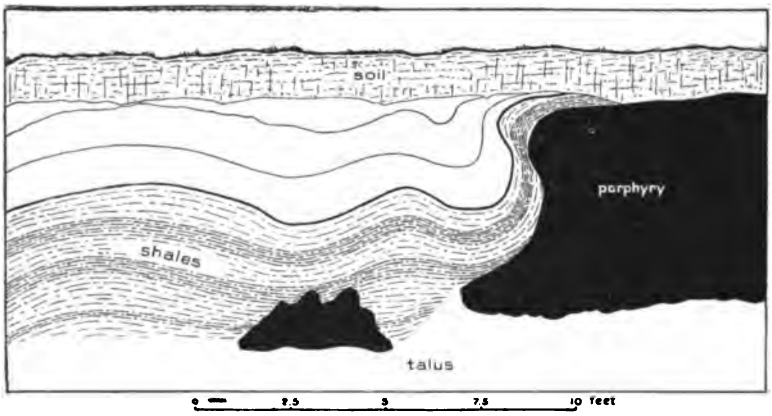


FIG. 88.—Deformation of shale by porphyry, Burlington Railroad, east of Whitetail Gulch.

TERRY PEAK.

Of the mountains made up of sills below, with a laccolithic remnant for cap, Terry Peak may be considered the type. None of these mountains can be called typical laccoliths, because the evidence for

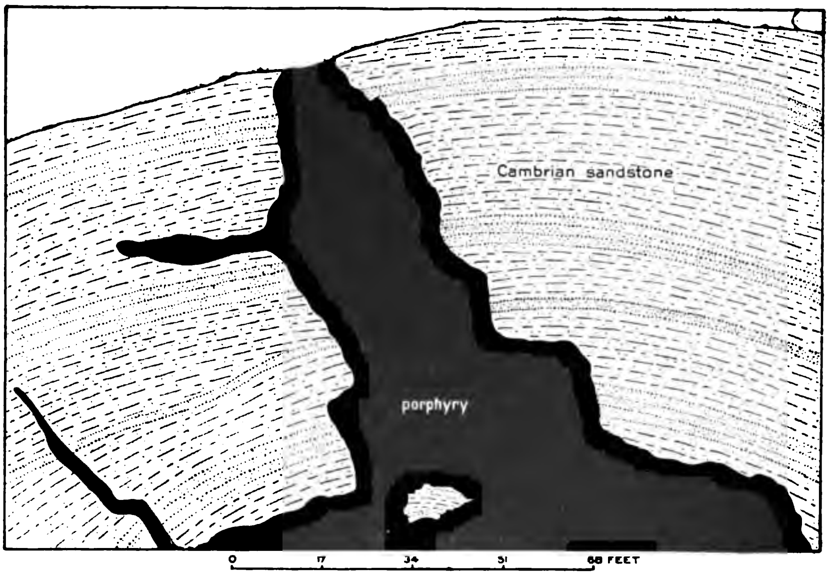
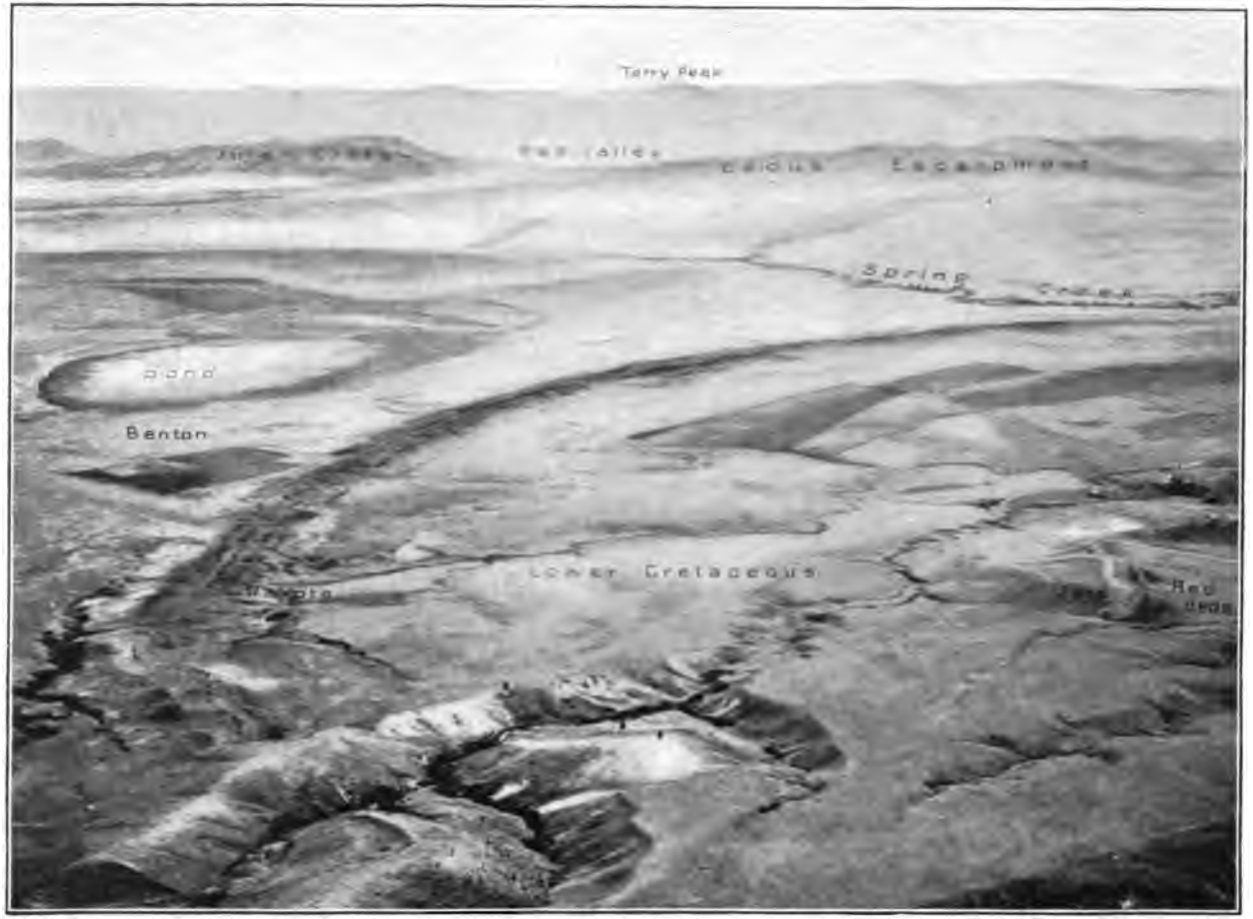


FIG. 89.—Irregular intrusions, north slope of Terry Peak.

their laccolithic structure based on flanking beds is almost invariably wanting by reason of deep erosion. A spur of the Terry Peak mass at the head of Raspberry Gulch retains a small remnant of Carbon-



CIRCUS FLATS, FROM BEAR BUTTE, LOOKING SOUTHWEST.

iferous limestone changing to the slope, which may indicate a former upper contact. The upper 300 feet of Terry Peak is of porphyry. Dikes, sills, and thick lenses of irregular form in Cambrian beds make up the rest of the mountain.

The railroad cuts and mines show many details of this structure. On the Burlington Railroad, near Aztec, a contact is shown with quartz-porphyry on the south and Cambrian shales and flagstones on the north, the contact curving from a wavy vertical line to a nearly horizontal one.

In the thick green shales at Portland porphyry intrusions of quite irregular form outcrop in a railway trench, some of these masses being almost elliptical in cross section and matching on opposite sides of the cut. Apparently the igneous material pushed its way through the shales in serpentine masses, like thickened lava on the slopes of a volcano, and such occurrences suggest strongly that the porphyry was very viscous at the time of its intrusion. The phenomenon is quite similar to that shown in Experiment I (fig. 101, p. 295), where the injected plaster spread irregularly in a layer of incoherent coal dust. Cases like this at Portland show that the shales, even when deeply buried under a sedimentary cover, offer as little resistance to the spread of an intrusive as they do to the action of the weather when exposed. They are inherently soft, whether subjected to superficial or subterranean tests. An illustration of this is shown at the bend of the railway east of Whitetail Gulch. Looking north in the cut (fig. 88), one sees that a dark-gray igneous rock with good vertical joints and very perfect horizontal lamellar parting has crumpled and distorted the shales. At the contact the cleavage in the porphyry bends to a west dip, parallel to the surface of deformation. In places the igneous contact followed curves of the deformed shale bedding, strongly suggesting extreme viscosity in the fluid at the time of its injection, and reluctance to follow any but the major stratification parting

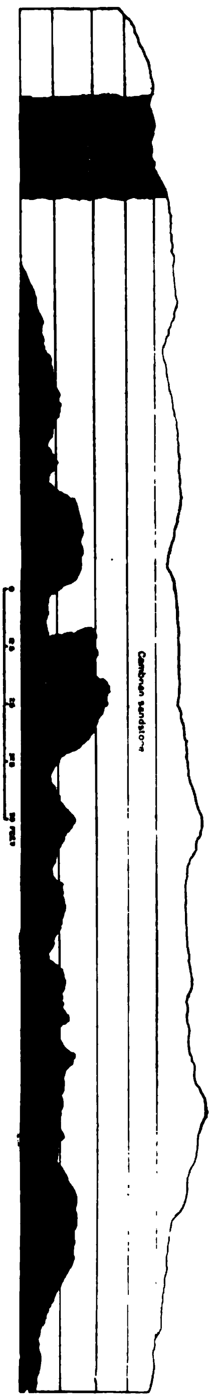


FIG. 90.—Section in railroad cut, north slope of Terry Peak.

the northern sedimentary rim of the Black Hills, thickened by porphyry. The straight divide seen in the middle distance is a mass of Tertiary and Pleistocene deposits

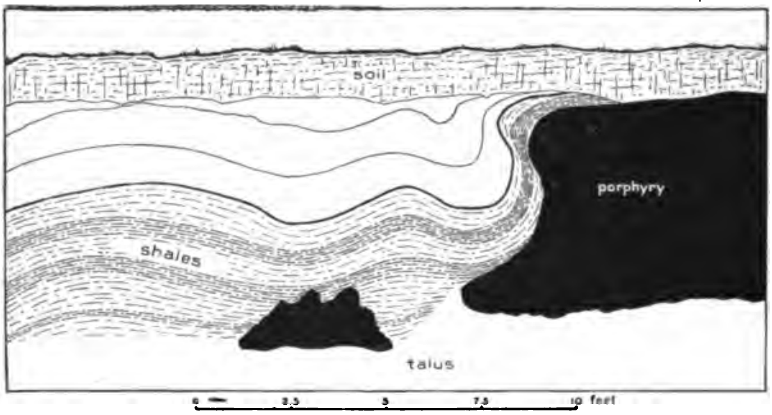


FIG. 88.—Deformation of shale by porphyry, Burlington Railroad, east of Whitetail Gulch.

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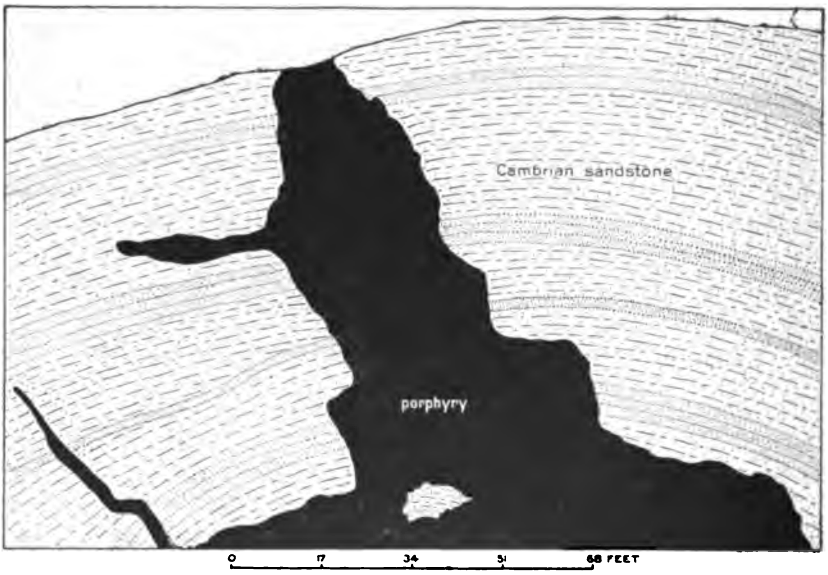

FIG. 89.—Irregular intrusions, north slope of Terry Peak.

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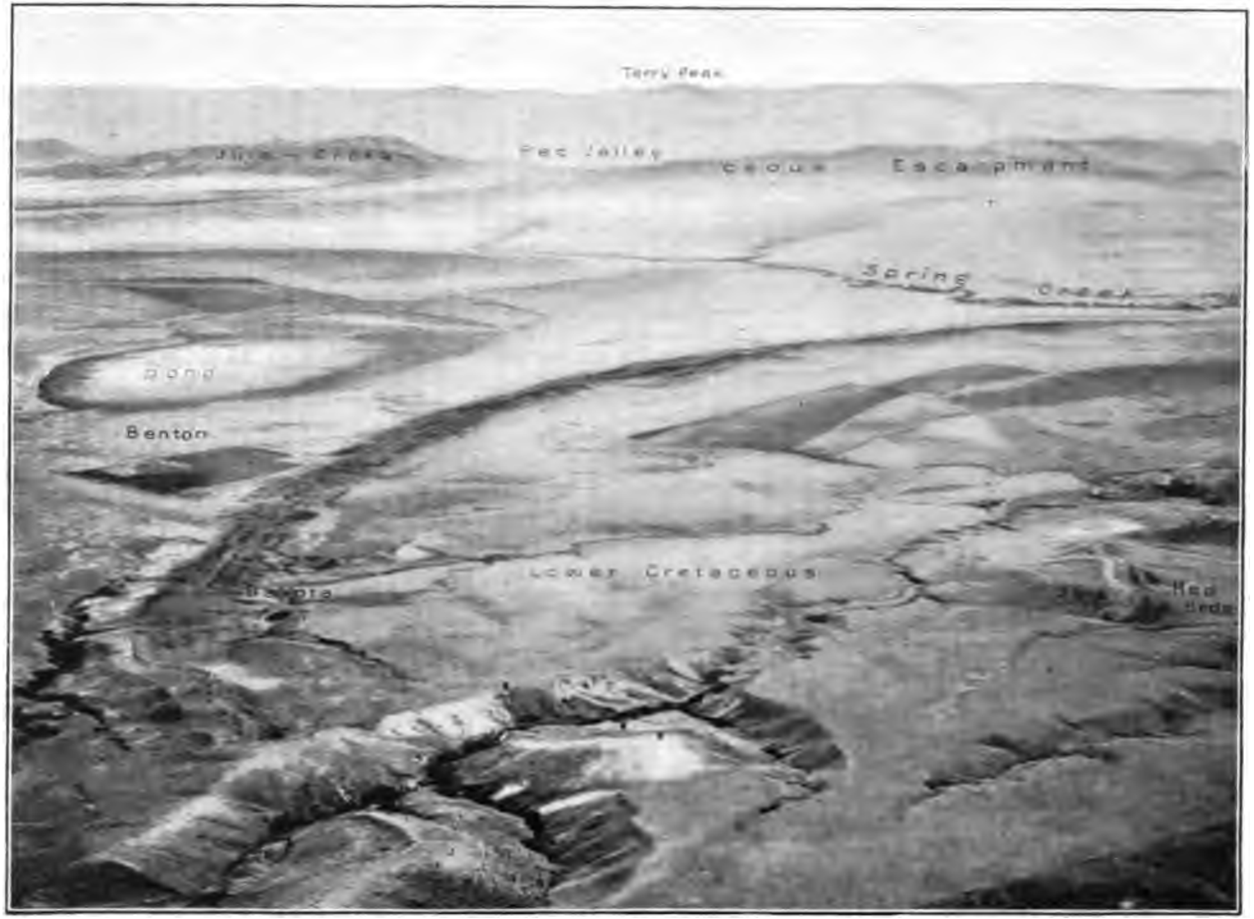

CIRCUS FLATS, FROM BEAR BUTTE, LOOKING SOUTHWEST.

additional features similar to the unsymmetrical Whitewood Canyon and Deadman laccoliths.

Sheep Mountain rises in the midst of the extensive northern porphyry area of the Terry-Polo complex, 2 miles northwest of Deadwood (Pl. XIX). On the crest of the ridge west of Sheep Mountain the Scolithus quartzite, characteristic of the top of the Cambrian, dips gently away from the mountain. On the south slope of Polo Peak, to the north, the same quartzite dips 65° southwesterly and overlies Cambrian limestone breccia and beds of calcareous and glauconitic sandstone. This dip is that of a bed upturned by the Polo Mountain porphyries. Rhyolite talus fills the hollows between Polo and Sheep mountains, but on such slopes the underlying bed rock is invariably masked. On the eastern slope of Sheep Mountain Scolithus quartzite, dipping eastward, overlies 40 feet of Cambrian beds, and in a small prospect hole the green shales, which are beds stratigraphically next above the quartzite, are seen to be cut across by coarse quartz-porphyry. On the southwestern spur of the mountain (fig. 91) this Scolithus quartzite dips S. 20° W. at an angle of 50°, but a few feet higher on the slope the *basal sandstone* of the Cambrian occurs, with fossils and pebbles, of entirely different aspect from the upper quartzite. This basal member may be traced around the mountain at about the 5,500-foot level, outcropping at six different points. On the west slope are intermediate Cambrian beds dipping southwesterly, showing brecciation and bending to a horizontal position. At one point west of the summit a fine-grained rhyolite was observed breaking upward and westward across glauconitic sandy beds, while the same beds were seen overlain by similar porphyry. The summit of the mountain is a green quartz-ægirine-porphyry, which seems to grade into a coarse white quartz-porphyry to the east and southeast. On the south side of the summit fine-grained rhyolite outcrops under the basal Obolus sandstone, and a shaft 40 feet deep on the slope above is cut in the green ægirine-porphyry to the Obolus sandstone beneath. These relations will be best understood by reference to fig. 91. The upturned Scolithus quartzite on the south, and the basal Obolus sandstone above forming a stratum beneath the porphyry cap, may imply a fault conduit on the south side, as in the Whitewood Canyon laccolith (Section B–C, Pl. XXI); otherwise, the mountain contains Cambrian and rhyolitic porphyries below and an ægirine-porphyry cap, and resembles Terry Peak.

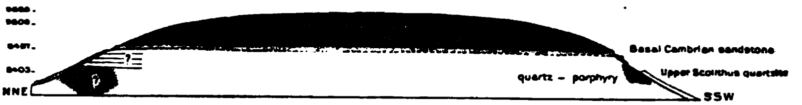

FIG. 91.—Section of Sheep Mountain.

LACCOLITHS.

True laccoliths in the Terry district, bearing to the sills and dikes below the same relation as that observed in the Deadwood district, are represented by Deer Mountain, Polo Peak, Spearfish Peak, Ragged Top, Citadel Rock, and Crow Peak. The masses originally laccolithic, but deeply eroded, are Custer Peak, Woodville Hills, Sugarloaf, Foley and Elk mountains, Little Crow Peak, and thick porphyry bodies north of Blacktail Gulch, at Carbonate, Lead, and at the head of Squaw Creek. Porphyry is revealed by the erosion of Spearfish Creek in its deep canyon at the mouth of Annie and Rubicon creeks and above the mouth of Squaw Creek; these occurrences may be sills or laccoliths.

DEER MOUNTAIN AND WOODVILLE HILLS.

Deer Mountain preserves much more perfect evidence of its laccolithic character than does Terry Peak. The whole group of peaks was known as the "Deer Mountains" by the Newton survey, and was described as follows:

> Terry Peak is the crowning point of an igneous region of considerable extent, having a maximum development in a northwest and southeast direction. * * * The peak stands upon the edge of the plateau. The Potsdam is extensively developed on its eastern side, and with it are occasionally outliers of the Carboniferous. Its sharply pointed summit is the most conspicuous landmark in the northern region of the Hills, and is visible from the plains far to the north and east. * * * The igneous group or range of which Terry is the highest point begins about 3 miles to the southeast, in a cluster of peaks called the Deer Mountains, and there is a nearly or perhaps quite continuous chain of trachytic and rhyolitic outcrops all the way to Terry. The same line continues northward for a few miles beyond Terry.
>
> The disturbance of the sedimentary strata is exceedingly local. * * * The sides of the ridge and of the peak are for the most part covered by a talus of angular and slippery fragments of rock (porphyry). On the summit of the peak the rock is well exposed, and three or four ridges of outcrop appear to radiate a few hundred feet from the central crest, while between them the slopes are composed of weathered fragments. * * * The igneous rocks of this region are varied in their appearance and texture.[1]

Deer Mountain is the southern rounded peak of the range and is a laccolith. The headwaters of Whitetail Gulch cut deep into the porphyry of its eastern slope. The greater mass of the Deer Mountain laccolith is exposed on the south and east slopes of the mountain, and monoclinal ridges or revet hills of limestone rest against the porphyry dome and dip away from it southwest, south, southeast, and east. Gulches along the contact of porphyry and sediments form a semicircular depression around the southern side of the mountain from Whitetail Gulch to Raspberry Gulch, occupied by small streams,

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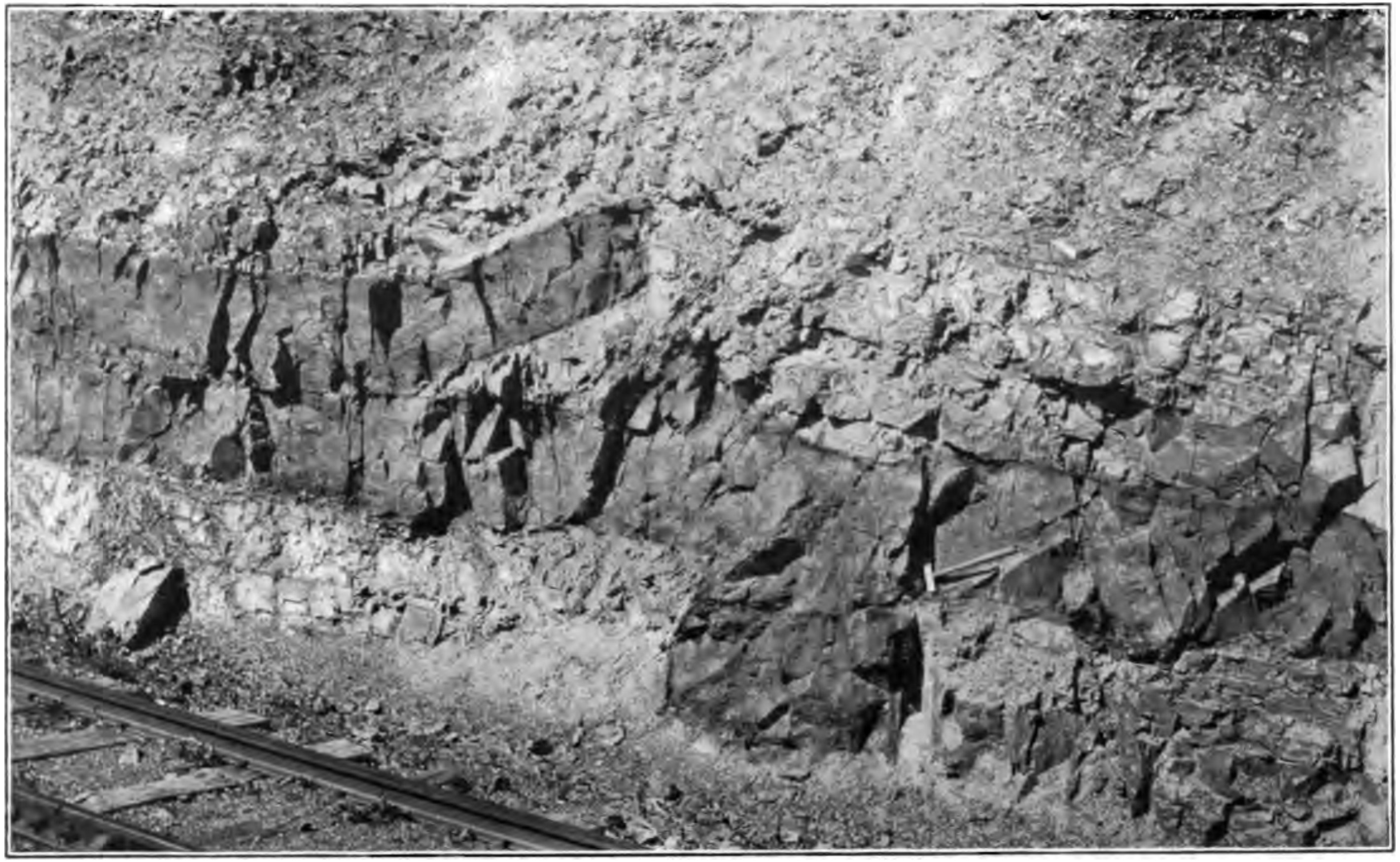
[1] Newton and Jenney, op. cit., p. 193.



JUNCTION OF DIKE WITH SILL. FREMONT RAILROAD. BALD MOUNTAIN.

It is apparent that the lower beds of the Cambrian were invaded by a mass of the fine white rhyolite over a very large area now laid bare down to the schist by the erosion of Bear Butte and Elk creeks. A hill one-half mile north of Brownville retains a Carboniferous limestone remnant dipping northeast over porphyry. Similar porphyry, and porphyry breccias, cap the adjacent hills at a distance from Custer Peak of 2½ miles. The synclines which separate Custer Peak from the Woodville Hills and the latter from Deer Mountain afford good evidence, in addition to physiographic proofs (see pp. 274, 276), that these three laccoliths were distinct, independent dome swellings under the great limestone, but the first two were also connected with a great mass of porphyry filling an anticlinal arch between Brownsville and Kirk and extending thence southeast for some distance. A chain of large dikes that were the conduits of this mass may be traced northward from south of Elk Creek, through West Strawberry, Whitewood (Pluma), Gold Run, and Deadwood creeks, to the mouth of Blacktail Gulch, where an immense dike is seen to bend upward into the thick porphyry mass that caps the ridge.

POLO AND SPEARFISH PEAKS.

The igneous masses extending from the greater Terry Peak and Deer Mountain laccoliths to the northeast reach their greatest development in Polo Mountain 3 miles northwest of Deadwood. From Blacktail Gulch north the hills are covered with porphyry, and the northward-flowing creeks have cut gullies through the igneous rock to Cambrian beds beneath. Along the divide at the head of Polo Gulch. Tertiary and Pleistocene clays and gravels occur in large masses, in part concealing the bed rock. In Sheep Mountain a complication of Cambrian and porphyry occurs as described. North of Sheep Mountain, Polo Peak rises to a height of 5,400 feet, and there is another summit north of it. Cambrian beds dip away on the southwest flank of Polo Peak, and occur under the porphyry in Miller Creek on the west, while on the east and southeast the limestones dip away from the irregular porphyry body, which, as a whole, was intruded in the shales beneath the Silurian. The intrusive of the northern peak, however, breaks across the limestone into Minnelusa beds, and the same is true of Spearfish Peak, 4 miles to the west.

The interstream ridges between Spearfish and Polo peaks are capped with porphyry, in part intrusive into the Carboniferous limestone and in part below it. The rock of Spearfish Peak is peculiar and was recognized by Caswell in Newton's report as a phonolite. It is probable that igneous bodies from west of Spearfish Canyon to Whitewood Gulch were continuous prior to the erosion that has separated them into cappings and north-dipping lenticular bodies in the several ridges.

The relation of Polo Peak as a laccolith to the greater masses that were probably once continuous northeast from Terry Peak is similar to that of the eastern portions of the Vanocker laccolith; the greatest difference lies in the fact that over the Polo laccolith the limestone, only 100 feet thick (Pl. XIX), was readily flexed upward as compared with the thick limestones of the vicinity of Runkel. Westward to Spearfish Peak the diminution of porphyries accompanies thickening of limestone. Eastward to Whitewood Canyon the Polo Mountain igneous masses thin to a single sill in the gulch opposite the smelter at Deadwood. East and west, isolated subordinate laccoliths have broken across the limestone, but the region from Deer Mountain to the northern extremity of Polo Mountain was the site of maximum irruption, and igneous fluids there filled the arch of a very large irregular anticline having an axis of north-south trend.

SUBORDINATE LACCOLITHS.

With the exception of Ragged Top, laccoliths demonstrably subordinate to the greater Terry-Polo masses, in the sense of being distinct offshoots, are wanting. The Whitewood Canyon laccolith, already described, is probably as closely connected with Polo Peak as with the Two Bit eruptives. Crow Peak and Citadel Rock, 4 to 5 miles west of the mouth of Spearfish Canyon, and hence west of the greater syncline, are as much related to the Iron Creek and Cement Ridge porphyries as to those of the Terry district.

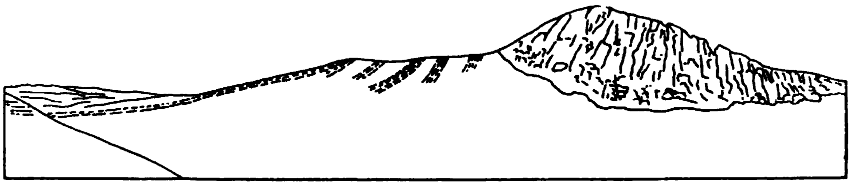


Fig. 92.—South side of Ragged Top Mountain (Irving).

RAGGED TOP MOUNTAIN.

Ragged Top is a steep laccolithic mountain, three-quarters of a mile long by one-half mile wide, its greatest length trending east and west, and its form a crescent with horns turned southward. It is about 3 miles west of Bald Mountain, and is surrounded by flat limestones. It has been figured (fig. 92) and described by Irving as follows:

> A little to the north of west and about 1 mile distant from Crown Hill, the low dome-like mass of Ragged Top Mountain rises some 400 feet above the level tableland of the Carboniferous plateau. It rises between the two confluent gulches of Calamity and Jackass creeks, the former shallow along the upper part of its course but becoming precipitous as it rounds the western end of the mountain. Here it unites with the more deeply carved gulch of Jackass Creek. Thence the two pass together between almost perpendicular walls of limestone into Spearfish Canyon. * * * In going upward from the west, north, or east [ascending the mountain] one passes over gently sloping strata of Carboniferous limestone which have an

> increasingly steep dip until within 250 feet of the summit. A rounded bluff of phonolite is then encountered, over whose crest one may readily climb and proceed up a decreasingly steep rise to the flat top of the hill. From this point the mass presents a somewhat unique topographic appearance, for it comprises two almost distinct roughly triangular masses of phonolite. * * * From both of these masses incurving tongues of phonolite run out to the south, circling toward one another so as to include and almost surround a large southwardly inclined amphitheater. * * * If one crosses Calamity Creek to the top of the limestone bench [at the west end of the mountain] the slight, almost imperceptible westward dip of the limestone may be seen to greatly increase as the phonolite is approached, until at the foot of the bluff, or about 20 feet distant therefrom, it has attained an angle of 51°.[1]

This is well illustrated in fig. 92. At numerous points about the mountain Cambrian shales are exposed, showing that the horizon of intrusion is the usual one, but so abrupt is the upward puncture made by the porphyry that it appears at a distance like a neck or a conduit through the limestone. Irving has shown that in a section revealed by the Badger shaft, on the north side of the mountain, the Cambrian shales lie against an almost vertical wall of porphyry, and have been followed to a depth of 316 feet. Irving's conclusion is as follows:

> On two sides, namely, to the east and south, the sediments have been worn away from the immediate neighborhood of the abrupt escarpment of phonolite. * * * On the west and north the sediments extend to the very foot of the igneous bluff, where they are upturned at a very high angle. On the very top of the mountain a small portion of Cambrian shale still remains.[2]

This arrangement is precisely what would be expected in a viscous subordinate mass breaking outward and upward to the west from the greater domes at the head of Squaw Creek. At the western end of the mountain the limestones are flexed backward sharply; at the eastern end they were lifted more gently, and perhaps somewhat fractured, as in the case of the Whitewood Canyon, Deadman, and Bear Butte laccoliths. It seems hardly necessary to postulate any considerable faulting to account for the present crescentic form of the mountain. The horseshoe shape accords perfectly with that of Citadel Rock and Inyankara (p. 274), and may be explained by simple erosive action resulting from the inheritance on the porphyry of annular drainage, superposed from domed sediments above.

CROW PEAK AND CITADEL ROCK.

Some 5 miles west and south, respectively, from the town of Spearfish are Crow Peak and Citadel Rock, two elliptical exposures of igneous rock, 2 miles apart, each about a mile long when measured northwest-southeast. Both dome up strata from Cambrian to Permian. Crow Peak, the more northerly of the two, arches the encircling beds more abruptly than does Citadel Rock. Crow Peak is a high mountain, Citadel Rock is an isolated butte encircled by a higher ridge of sediments of horseshoe shape. The summit of Crow Peak rises 5,785 feet above the sea; Citadel Rock, 5,450 feet. The relation of these two is not unlike that of Circus Flats and Bear Butte. Circus Flats marked the lower main laccolith of which Bear Butte was a subordinate upshoot. Crow Peak, which strongly resembles Bear Butte, may be subordinate to a large subterranean mass of which merely the crest is revealed at Citadel Rock.

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[1] A contribution to the geology of the northern Black Hills, by John Duer Irving: Annals New York Acad. Sci., Vol. XII, No. 9, pp. 212-214.

[2] Op. cit., p. 217.

Crow Peak is the highest point in the northern Hills lying so near to the Red Valley. Its proximity to the plains gives to its relief excessive prominence. Seen from the east (Pl. XXIX) the conspicuous elements of its profile are a sharp conical southern peak of porphyry and a steep monoclinal scarp of limestone resting against it on the north side. Thrust up through the limestone where the sediments had long, gentle dip slopes northward, the igneous core is completely revetted with rounded imbricating monoclinal ridges of Silurian and Carboniferous limestone dipping steeply away on all sides (Pls. XIX and XLI). Wherever the contact was examined closely Cambrian beds were found, and on the north side peripheral sills in Cambrian occupy the hollows in the bend, as figured in the original (Henry Mountains) laccoliths. Dips taken while ascending a gulch on the north side of the mountain varied from horizontal one-half mile north of the mountain to 27°, 40°, 65°, and 89° in Minnelusa, gray limestone, and Cambrian beds. A tunnel at the head of the gulch, cut horizontally for 110 feet southwest into the mountain, passes through 105 feet of porphyry and penetrates for 5 feet at the end a bed of quartzitic sandstone dipping 12°, N. 20° W. The contact of the porphyry with this sandstone is ragged and trends NNW. The sandstone shows *Obolus* and evidently represents the lowest of the Cambrian beds. From this it would appear that the whole Cambrian section is upturned to the northwest by the Crow Peak uplift, and the porphyry traversed by the tunnel appears to be a steeply upturned cross-cutting sill or dike.

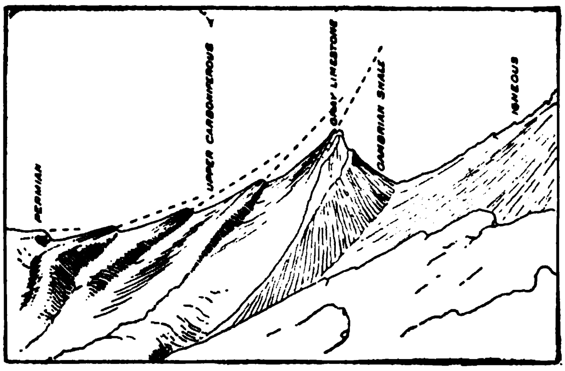

FIG. 93.—South slope of Crow Peak, showing change of dip.

The summit of Crow Peak is a sharp edge like that of Bear Butte, trending northwest and running out into a knife-edge, with spurs flanked by steep talus slopes and precipitous walls. High on the east side the sediments lap against the steep laccolith, dipping 51° to the east, and the limestone shows small faulting with western upthrow. On descending the east slope, beds from Cambrian to Minnekahta limestone (Permian) are crossed in a distance of one-half mile, and the transition to low dips and horizontality is very sudden. The most striking revet crags are seen on the south side of the mountain, where they form crescentic ridges with bare limestone crests, separated from one another by V-shaped trenches that give passage to rills which regularly fork into two within the V along the porphyry-Cambrian contact. Fragments of brown sandstone and Scolithus quartzite occur near the porphyry, and in a few hundred yards the geologic section from Carboniferous to Permian shows a change in dip from 60° to 0° (fig. 93). This sudden change of dip in consecutive outcrops of overlapping strata is characteristic of the steeper laccoliths (see fig. 92), and the distance in which the change takes place is sometimes actually less than the normal thickness of the beds involved. The structure shown would not permit uniform curvature of all the strata over the dome. The only explanation for such structure is that there has been rupture of the hard beds, with stretching, compression, and flow in the soft beds. The soft beds thicken in the concavities and thin on the arch. Crow Peak is encircled on the east, south, and west by Higgins and Crow creeks and their tributaries; on the north a flat upland slope of Minnekahta limestone extends out to the Red Valley, where it abruptly bends downward, while Minnelusa sandstone forms a ridge to the northwest, with anticlinal structure, suggesting the extension in that direction of an elongate subterranean tongue of igneous rock from Crow Peak. The very rapid bend from steep upturning to horizontality is well shown by the present attitude of the Minnekahta limestone, which completely encircles the mountain in nearly horizontal tables, and makes a broad spoon synclinal on the south side (Pl. XLI).

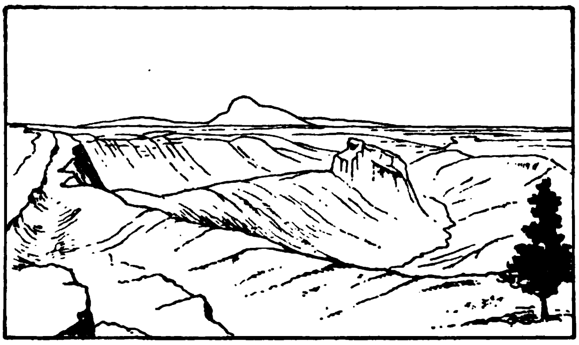

FIG. 94.—Citadel Rock, looking northward toward Crow Peak.

Citadel Rock has been uncovered by erosion in much the same fashion as Circus Flats. Branches of Robison, Johnston, and Higgins creeks have so eroded the dome of limestone that was above the laccolith that the Minnelusa cover is removed, and one north-flowing stream has breached the gray limestone and Cambrian; with its headwater forks it has eaten out an annular valley in the porphyry about a spur which has a columnar castellated tower rising in the center; the crest of the "Citadel" is 400 to 500 feet above the gulches on either side (fig. 94, Pl. XLI). The northern end of the Citadel Rock spur still retains a veneer of Cambrian beds. The Cambrian, Silurian, and Carboniferous section is clearly shown in the horseshoe rim of sediments that incloses the annular valley, and within this rim, on the southeast side of the basin, a sill occurs in the Cambrian. The columnar Citadel is connected with the encircling escarpment by a singularly straight ridge of porphyry; the limestone horseshoe rises to a height of 200 feet above the summit of Citadel Rock.

It is clear that Crow Peak stands high by reason of the steep inclination of peripheral contacts and the great height of the porphyry topographically, whereas Citadel Rock, topographically lower and with contacts less steep, has until very recently been subjacent to easily eroded Cambrian shales, which were hollowed out as a basin beneath the salient, hard Carboniferous limestones and sandstones. So completely is the Citadel concealed within its encircling rampart of forested hills that it has never been noticed by earlier geological explorers, although the actual area of porphyry exposed is almost as great as that of Crow Peak.

SUMMARY OF TERRY DISTRICT.

The Terry district of laccolithic porphyries contains types characteristic of a deeper zone than the Two Bit district, just as the Two Bit district is stratigraphically lower than the Vanocker district. The conspicuous features of the Terry-Polo complex are conduits and eroded remnants of laccoliths. Erosion has gone deeper because the region as a whole is higher. Conduits are represented by stocks in schist and by innumerable dikes which follow Algonkian lamination. Some of these filled fissures inclined west, others east. The one set spread to the east and the other to the west when the porphyry reached fissile, flat-lying Paleozoic beds. Sills were formed in the Cambrian, and these thickened into laccoliths. By reason of a thinner Cambrian section, sills were less numerous and thicker than in Two Bit. The major laccoliths are preserved with their flanking strata in the edge of the Carboniferous plateau and in the northern Paleozoic escarpment. Eruptive masses like Spearfish Peak broke outward and upward across initially dipping limestones. A characteristic type of mountain left by erosion is dome shaped, with a laccolith cap, and sills below. The

Terry intrusives as a whole occupied a great arch between Spearfish Creek and Whitewood Creek, beneath an axial line of thinnest limestone. Where the limestone broke on the flanks of the arch the rupture gaped below, and viscous magma oozed out through the fractures, to harden in small domes of intense flexure, like Ragged Top. To the northwest, in the general trend of Custer Peak, Woodville Hills, Deer Mountain, Terry Peak, and Ragged Top (a trend parallel also to the dikes), masses of intrusive rock rise through Upper Carboniferous and Permian limestone to form a lower southern laccolith, Citadel Rock, barely breached by erosion, and a higher and steeper northern one, Crow Peak, that forces up the sediments steeply about its flanks.

LACCOLITHIC INTRUSIVES OF SUNDANCE DISTRICT.

The Sundance district contains two greater centers of igneous activity. The one on the east resembles somewhat the Terry district, containing rocks from Algonkian to Permian, with dikes, sills, and laccoliths. This has been called the Cement Ridge complex, the name being that of the highest porphyry summit, a forested peak comparable to Terry Peak in its position at the edge of the limestone plateau. Large masses of porphyry, the main laccoliths, occur about the headwaters of Beaver Creek and Iron Creek, and Black Buttes, somewhat separated from the rest, forms a laccolithic uplift of considerable size adjacent to the Red Valley on the west side of the Black Hills. Subordinate laccoliths are the Needles on the north, and Spottedtail Dome and Inyankara Mountain on the west.

The second igneous center is the Bearlodge Range, an elongate uplift of Paleozoic rocks with igneous core, trending northeast and southwest, lying northwest of the Black Hills uplift proper, and separated from it by the Red Valley at Sundance. Subordinate to the greater medial intrusion, which reaches its culmination in the Warren Peaks, minor laccoliths have broken through Mesozoic beds on both flanks of the range; these form the Sundance Hills on the southeast and the Little Missouri Buttes and Mato Teepee on the northwest.

The data recorded here for the Sundance district were obtained during a reconnaissance of two weeks' duration in October, 1898, made with a view to comparing the igneous phenomena of the northwest with those more thoroughly studied in the Deadwood and Terry districts. In this excursion the writer was efficiently assisted by Dr. J. D. Irving. The Cement Ridge country, Black Buttes, Inyankara, Sundance Hills, and Warren Peaks were accorded very brief examination en route to Mato Teepee, where a longer stay was made in order to settle, if possible, disputed questions concerning the origin of that extraordinary monolith and its companion hills, the Little Missouri Buttes.

CEMENT RIDGE COMPLEX.

LACCOLITHS.

CEMENT RIDGE AND IRON CREEK.

Topographically Cement Ridge, 2 miles south of Welcome, extending as a height of land far to the south, marks the same sort of culminating porphyry center as Terry Peak to the east and Warren Peaks to the west; it forms the divide from which streams flow east to Spearfish Creek and west to the Grand Canyon. West of Cement Ridge the stratified rocks dip away very gently, the Minnelusa sandstones of Spottedtail, Rattlesnake, and Cold Springs valleys appearing almost horizontal and exposed for great distances. It was in one of these valleys farther to the south that Winchell first saw the Minnelusa rocks, and he gave the Indian name of the creek to the formation. The wide valley formed by the "Red Beds" south of Sundance shows a striking symmetry of topographic forms on either side. To the northwest are seen the long level summits of the Bearlodge Mountains, with the two laccolithic outliers, Sundance Mountain and Green Mountain ("Little Sundance Dome") in the Red Valley at their feet. To the east Cement Ridge forms a similar long crest, with Black Buttes rising abruptly from the Red Valley at its foot; and north of these buttes occurs a long dome, hitherto not noticed by geologists, that corresponds in position on the eastern side of the valley to Green Mountain on the western. This hill, here called the Spottedtail Dome, is encircled by a rim of Minnekahta limestone, as in the case of Green Mountain (Pl. XVIII).

The summit of Cement Ridge is porphyry, apparently intruded about the base of the Cambrian, for the basal quartzite of that formation forms a ledge dipping at a low angle off the mountain on the west at the head of Rattlesnake Creek, and conglomerate underlies the porphyry on the east side. About the head of Beaver Creek the country is densely forested and shows but few outcrops. The float is Cambrian and porphyry. Large laccolithic bodies occur on Iron Creek south of Bear Gulch. These again are in part intruded at the base of the Cambrian, for the basal conglomerate overlies them (Pl. XIX). Iron and Deer creeks flow east to Spearfish Canyon. They apparently drain the eastern flank of a laccolith of large size and relatively gentle curvature. The region between Bear Gulch post-office and Cement Ridge shows alternations of Algonkian, Cambrian, and porphyry, indicating the presence of many dikes and sills. The dikes west of Bear Gulch have a general NNW. trend, and the usual tendency of the porphry to form hill cappings was observed, as at Lead, indicating the presence of eroded remnants of sills and laccoliths.

BLACK BUTTES AND SPOTTEDTAIL DOME.

Newton mentioned "a nameless peak northeast of Inyankara," composed of igneous rock. This igneous mass proves to be a group of hills of some size, containing laccolithic intrusions in strata ranging from Cambrian to Permian. The Black Buttes must not be confused with "Black Butte," an old name for Spearfish Peak. They lie west of Cement Ridge, separated from it by a wide area of Minnelusa beds lying almost horizontal, so that they form a separate center of irruption.

The Black Buttes are a group of hills composed of porphyry, which breaks through and uplifts by intrusion stratified sediments from Cambrian to Red Beds. Approaching the Buttes from the northern side, one observes that the several radial creeks have cut V-shaped trenches in Minnekahta limestone and Minnelusa limestones and sandstones. Looking to the north from the summit of the northern butte, the Minnekahta limestone on the eastern border of Red Valley is seen to lie rather flat, conforming to very gentle dips noted in the valleys on the western flanks of Cement Ridge. Three and a half miles to the north, however, is seen the long, low, Spottedtail Dome, exposing Minnekahta limestone dipping away in both directions, and a Minnelusa core in a long ellipse of northwest-southeast axis. The northern hills of the Black Buttes are three in number; the two western ones are sharp, conical peaks of porphyry; a more elongate one to the east is composed of Carboniferous limestone. On the northern side of the middle hill porphyry was found directly in contact with Minnelusa sandstone, here indurated to quartzite. From the summit of the hill the Black Buttes are seen to be an irregular group of hills, occupying an area of some 20 square miles. The hills inclose basinlike depressions, and in one of these were found prospecting tunnels and shafts cut through glauconitic and calcareous Cambrian shales.

The porphyry breaks across strata from east to west, forming intrusive sills and small laccoliths at progressively higher horizons. Gray limestone is uplifted by the porphyry in the peak farthest to the southwest. In the Cambrian shales mentioned a small dome was traced in three outcrops, the quaquaversal curvature being indicated by radial dips. There are numerous small conical porphyry-capped hills, producing topographic irregularities in the inner basins. In a tunnel about the central portion of the Black Buttes an upright contact of porphyry and gray limestone was found. The section through the uplifted limestone on the southwest is similar to that through the Deadman laccolith (Pl. XXI, F–G), with the difference that, in the Black Buttes, Minnelusa sandstone dips under the porphyry instead of being beveled across by it (Pl. XXXVI). The Black Buttes as a whole form a small isolated igneous center, involving all the Paleozoic rocks, the porphyry spreading outward and stratigraphically upward toward Inyankara. Inyankara Mountain is undoubtedly an offshoot of the greater Black Buttes laccoliths. Spottedtail Dome may cover a large laccolith somewhat analogous in position to that of the Black Buttes and possibly on the same line of conduits beneath, but the porphyry lies topographically too low to be dissected by the present drainage, and hence is not as yet revealed.

Subordinate Laccoliths.

THE NEEDLES.

A porphyry mass between Beaver Creek and Bear Gulch, passing into large dikes southward, is locally known as "The Needles," or Connors Peak. This eruptive body shows characteristics similar to some of those of the better-known laccoliths, but the hills being densely wooded and the rocks little exposed it is difficult of investigation without extended study. The eruptive cuts Carboniferous limestone on the north and east, and upturned Cambrian strata are seen on the west and south, while porphyry occurs on the southwest directly in contact with the coarse pegmatite and schists of Nigger Hill. There is thus a region of vents through the Algonkian exposed in this Nigger Hill district, and dikes of porphyry cutting the Algonkian rocks are found farther south on the main road to Welcome. In general the Needles may be described as a mass of porphyry of irregular form breaking across beds from Cambrian sandstone on the south and west to Carboniferous limestone on the north and east. Its castellated pinnacles form a prominent feature in the landscape.

Irving describes the Needles as follows:[1]

> This porphyry uplift * * * consists of a series of extremely sharp conical peaks * * * which show the most perfect columnar parting that the writer has seen in the Hills, with the exception of those exposed in the Devil's Tower. The columns are vertical, and are broken across by a jointing which shows a rough resemblance to the ball and socket jointing of basalt. Three of these conical peaks are especially high, one of them rising 500 feet above the bed of the creek below.
>
> Viewed from the south, they bear, collectively, strong resemblance to a huge dike, but on ascending the highest of them, one is impressed with the almost plug-like character of the mass. The Carboniferous limestone can be seen to the east, north and northwest, forming a wall about the uplift. On the west there seems to be an extension of the porphyry. On the south great blocks of indurated sandstone occur and the Cambrian is extensively exposed in this direction. * * * In between the lower porphyry hills exposures of Cambrian shale occur, as if in its intrusion the rock had included a portion of that series above itself, and had elevated this to the level of the surrounding limestone. [Compare Sheep Mountain, Dome Mountain, and Whitewood Canyon laccolith, fig. 91 and Pls. XX and XXI.]

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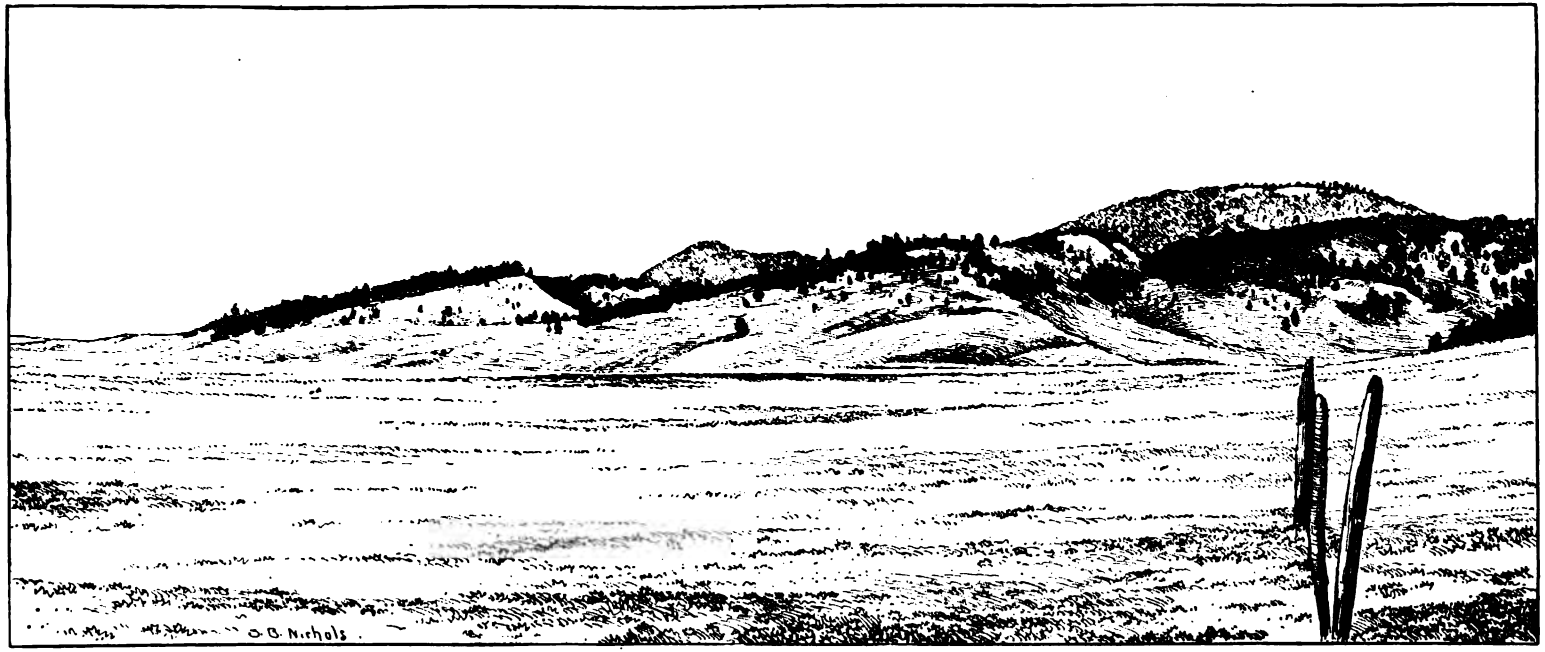
[1] A contribution to the geology of the northern Black Hills, by J. D. Irving: Annals New York Acad. Sci., Vol. XII, No. 9, p. 224.



BLACK BUTTES, FROM THE SOUTHWEST.

It will be seen from this description that the Needles are a subordinate laccolith like Ragged Top, flexing back the massive limestone on the side remote from the greater Cement Ridge masses, and were injected probably in a highly viscous condition through the Cambrian beds on the northern border of the larger southern laccolith. Lying a short distance west of Crow Peak, the Needles occupy a similar position structurally. The rock of the Needles is somewhat unusual—a diorite-porpyhry without mica, containing phenocrysts of automorphic hornblende, sanidine, and plagioclase in a groundmass of plagioclase, magnetite, and orthoclase.

INYANKARA MOUNTAIN.

Inyankara Mountain was described by Winchell[1] more accurately than by Newton. The mountain rises on the outer side of the Red Valley 4 miles southwest of Black Buttes. It has a height of 6,313 feet above the sea and some 1,400 feet above Inyankara Creek, which curves in a semicircle around the north side of the mountain. Its striking circular symmetry—a cone in the middle of a horseshoe ridge—has been variously compared to a hat, saucer, etc. Winchell describes the mountain as follows, and the observations quoted accord with the writer's:

> Its summit, which rises high enough to mark it as an important peak among the hills that surround it, has the shape of an inverted saucer, with another smaller inverted saucer lying on the top. * * * Before reaching it we pass over three or four foothills, composed of Jurassic and Cretaceous. * * * These formations are not greatly disturbed by the uplift, but still show a very perceptible dip away from the mountain. At the foot of the mountain * * * we enter upon the Carboniferous limestone, which has a dip of about 30° from the horizontal, varying from 20° to 60°, sometimes presenting shoulders that have a confused dip, or stand vertical. Over this we climb to a height of about 500 feet to the top of a circular ridge which incloses the main columnar center of the mountain. * * * Crossing a wooded glen * * * we ascend the peak from the south. The shape of the summit, which at a distance has the aspect of a small saucer lying on a larger one, both inverted, is caused by the central mass rising above the rim or ridge, by which it is nearly surrounded. The only opening in this rim is towards the north 10° east, where it is entirely wanting. The ridge is about three-quarters of a mile distant from the central mass, in all directions, and gives the outline of the larger saucer. It does not rise as high as the central mass. * * * The intervening space is occupied by a dark valley, narrow, and shaded with Norway pines. It is very difficult, and in many places impossible, to pass from the ridge to the center across this gorge, the rock rising sheer up on nearly all sides about the central mass. * * *
>
> The Carboniferous limestone seems to be warped into a wave-like surface when exposed on some of the lower flanks, a fact also noticed at other places, and lies at a high angle of incline all about the mountain's base. The rock * * * is igneous, thrust through the sedimentary strata. There is a very marked system of perpendicular jointage planes that cut the main ridge east and west, the individual planes

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[1] Geological Report on the Black Hills, by N. H. Winchell: Reconnaissance of 1874, by Captain William Ludlow, Engineer Department U. S. A., Washington, 1875, p. 17.

being about 10 inches apart or closer. Another system runs northeast and southwest, the planes being 4 feet apart, and tipped (their tops) toward the southeast about 10°; while a third system runs perpendicular to the last, and has the tops inclined toward the northeast about 10°. These larger divisions of the rock cause, on being weathered, the columnar structure seen all about the sides of the central mass. There is, besides, on the western side of the central mass, a fourth system of joints, that slope toward the west at an angle of about 45°, which gives the whole mass at that point the appearance of being a heavy-bedded, upheaved sedimentary rock. * * * The east side of the horseshoe ridge is made up of much the same kind of rock, but weathers whiter. It is very much cut up by divisional planes, and stands up in vertical dike-like ridges in some places on the east and southeast.

Newton failed to recognize the Carboniferous or Jura-Cretaceous in the encircling beds, nor did he note that the horseshoe rim is formed in part of porphyry. He was under the mistaken impression that the purple Permian limestone and the Red Beds were the only strata affected by the igneous uplift, and that this same limestone formed the annular ridge. The annular valley about the central porphyry core has been commonly supposed to represent the contact between porphyry and sediments. The writer visited the rim of this valley, and the first ridge outside of the deep gorge that surrounds the central eruptive dome proved to be porphyry, as stated by Winchell, a case by no means uncommon in these laccolithic masses, and resulted from the superposition on porphyry of an annular valley originally formed in sediments (see Citadel Rock, fig. 94). The Inyankara horizon of intrusion, so far as revealed by the eastern contact, is the Minnelusa formation, which here forms a dense white quartzite in contact with the porphyry. One or two sills of porphyry were crossed in their normal position, i. e. the angle formed by buckling of strata about the base of the uplift. The hard and soft beds of Minnelusa, Permian, Trias, and Jura form a series of concentric ridges and valleys inclosing the inner porphyry dome.

Inyankara Mountain represents a stage in denudation much like that of Citadel Rock. It is, however, a steeper dome, intruded stratigraphically higher, and may be classed genetically with Crow Peak and Bear Butte. It is probably subordinate to the greater mass of the Black Buttes. Relative to Bear Butte and Crow Peak it represents an earlier stage of uncovering by erosion. In future centuries the flanking sediments will wear lower, the porphyry will assert its more resistant quality and stand in much greater relief, and the annular valley will lose definition until it persists only in the mountain profile, which will remain divided rudely into three parts, a central high summit and irregular lower ridges on either side (see fig. 97).

BEARLODGE COMPLEX.

LACCOLITHS.

The greater porphyry masses of the interior of the Bearlodge Range may be considered the principal laccoliths to which the Sundance Hills are subordinate. It is not clear that Little Missouri Buttes and Mato Teepee are subordinate to the Bearlodge core in the same sense, for, as will be shown, there is good reason for the belief that Mato Teepee is a subordinate extension from the Little Missouri Buttes as a center. In this case the spread of the igneous magma was southeast, toward the Bearlodge Range, instead of away from it. As the rock of the Little Missouri Buttes and Mato Teepee is lithologically very different from known specimens from the Warren Peaks and Sundance Mountain, and contains inclusions of the older rhyolitic porphyries, it is probable that the Little Missouri Buttes laccolith was injected independently of and later than that of Warren Peaks. This is borne out by evidence which shows that the dip of sediments away from the greater Bearlodge uplift existed at the time of the Mato Teepee intrusion. It is probable that both of the greater intrusions came up through fissures in the Algonkian inclined eastward from the vertical, and therefore had a tendency to spread onward to the east. In this sense, then, Little Missouri Buttes must be considered the main laccolith to which Mato Teepee is subordinate. Both will be treated together here, however, as subordinate laccoliths to the Warren Peak mass.

WARREN PEAKS.

The Bearlodge Range proper has been fully described by Newton[1] and Jenney,[2] and this description needs no repetition in detail. Warren Peaks, the highest summits of the range, are bare, rounded, grass-covered hills of coarse granite-porphyry, reaching a height of 6,654 feet above sea level. Seen from east or west the peaks are not conspicuous, because the slopes are long and gentle. The structure, which has been called a miniature copy of the Black Hills, is that of an elongate laccolithic uplift extending about 20 miles northeast and southwest, with a porphyry core exposed for 8 miles. Subordinate intrusions occur on the flanks, where rocks from Cambrian to Jura-Cretaceous dip away in all directions. Northwest and north the trunk drainage from the range flows radially to the Belle Fourche River. Rectangular systems of branch streams are formed by subsequent development along soft strata. The Minnekahta limestone forms on the slopes its characteristic V-shaped gateways. Seen from Mato Teepee on the northwest, a larger valley on the slope of the

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[1] Report on the Geology and Resources of the Black Hills of Dakota, by Henry Newton and Walter P. Jenney: U. S. Geog. and Geol. Surv. Rocky Mountain Region, Washington, 1880, pp. 199.

[2] Op. cit., p. 283.

Bearlodge Range shows three pairs of benches; one bounds a wide, flat valley above; a lower trench corresponds with the present valley of the Belle Fourche; and a smaller, lowest trench suggests a recent uplift. The highest bench is formed of Lower Cretaceous strata; the next lower of Jurassic. A columnar sill was found high on the northwest slope of the range in Jurassic ripple-marked sandstones. On the east side of the range the canyons are deep and the dips higher, sometimes between 30° and 40°.

SUBORDINATE LACCOLITHS.

SUNDANCE HILLS.

In the Red Valley southeast of Warren Peaks two laccolithic hills occur, occupying on that side of the Bearlodge uplift a position symmetrical to that occupied by Mato Teepee and the Little Missouri Buttes on the northwest side. The Sundance Hills appear to be outliers, bearing to the greater laccolith the relation of lateral lenses in normal subordinate position, filling the bends and injected through peripheral concentric fractures (Pl. XLIV). They have been described by Newton[1] and Russell.[2] The southern and larger mass, Sundance Mountain, is composed of porphyry, intruded through Permian and Trias to Jura on its eastern side, hence probably injected from the west, i. e., from the direction of the Bearlodge Range. Porphyry cliffs occurring across Sundance Valley on the western side of the town appear to be the sheet of which Sundance Mountain is the thickened eastern termination.

The porphyry of Sundance Mountain, a fine-grained rhyolite, shows at a distance a yellow-greenish color, induced by a characteristic lichen noted both here and on Mato Teepee in great abundance on the face of the vertical cliffs. The porphyry extends in an irregular lobe from the main mass of the mountain to the westward, where rounded low hillocks covered with porphyry slabs occur at levels a hundred feet or more lower than the Red Beds on the northern face of the mountain. A hundred yards to the north the Red Beds, entirely free from porphyry débris, dip 14° under the mountain S. 60° E. There is thus evidence on this side of the eruptive breaking across Minnekahta limestone and Red Beds. The Red Beds recur at the foot of the mountain on the north, without any appearance of dipping away from it, showing distinct horizontal bedding. Jurassic beds occur east of the mountain. On the flanks of the Bearlodge Range to the northward the Minnekahta limestone dips southeast, the south-flowing drainage cutting through it the usual V-shaped gateways. The dome of Green Mountain (Little Sundance dome) is remarkably symmetrical and isolated, but in structure is altogether similar to Elkhorn or Spottedtail dome, with a Minnelusa crest and an encircling shell of Permian limestone. A short distance west of Sundance there is a dome-shaped hill which appears to be another buried laccolith like Green Mountain.

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[1] Op. cit., p. 197.

[2] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, 1896, p. 29.

LITTLE MISSOURI BUTTES AND MATO TEEPEE.

Descriptions by previous writers.—Jenney wrote as follows,[1] describing the appearance of Little Missouri Buttes and Mato Teepee (see fig. 95) from the summit of Warren Peaks:

> To the west (magnetic), some 20 miles away, Bear Lodge Butte [Mato Teepee] and the Little Missouri Buttes appear in line. From this distance the former resembles in appearance the huge stump of a tree, its surface curiously striated vertically from top to base, and, being perched on the crest of a high, flat-topped ridge, it becomes a very prominent landmark, which, once seen, is so singular and unique that it can never be forgotten. Although the Bear Lodge country is an elevated region, and the different streams have a considerable fall before reaching the Belle Fourche, yet the topography is quite peculiar in the prevalence of long, flat-topped ridges or mesas between the narrow and deep valleys and canyons of the creeks. This is due to the resistance to erosion offered by hard and continuous strata of sandstone of the Jurassic and Cretaceous formations, which are here almost horizontal in their bedding, with a gentle slope away from Warren Peaks.

That part of Newton's description which accords with the writer's observations may be quoted:[2]

> *The Bear Lodge* (*Mato Teepee*).—This name appears on the earliest map of the region, * * * though more recently it is said to be known among the Indians as "the bad god's tower," or, in better English, "the devil's tower." * * * It stands on the immediate western bank of the Belle Fourche, about 4 miles southeast from the Little Missouri Buttes. It was not reached by the Warren expedition, but while the Raynolds expedition was in the vicinity of the Little Missouri River two attempts, the last successful, were made by Mr. Hutton to reach it. He recorded, however, no particular description of it, so that when we reached it in 1875 our examination had all the charm of novelty. Its remarkable structure, its symmetry and its prominence made it an unfailing object of wonder. It is a great rectangular obelisk of trachyte [phonolite] with a columnar structure, giving it a vertically striated appearance and it rises 625 feet, almost perpendicular, from its base. Its summit is so entirely inaccessible that the energetic explorer, to whom the ascent of an ordinarily difficult crag is but a pleasant pastime, standing at its base could only look upward in despair of ever planting his feet on the top.[3] * * * Within a half mile of the banks of the Belle Fourche the shaft rises with its broad base of débris from the plateau formed by the lower Jurassic sandstone. Its dimensions were

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[1] Op. cit., p. 284.

[2] Op. cit., p. 200.

[3] Both Newton and Russell remark on the absolutely inaccessible character of the summit. Russell says, "The strongest and most experienced mountain climber must pause when he has scaled the rugged cliffs which form the immediate base of the tower and gains the point where the individual prisms make their abrupt curve and ascend perpendicularly. Beyond that point no man has ever reached, and, it is safe to say, never will, unaided by appliances to assist him in climbing." Such appliances have recently, however, been used; with the aid of iron bars driven into the angle between two sloping columns, a rude ladder was constructed by an enterprising climber, and the ascent to the summit has been made, a fact attested by a small flag, visible from below, which was left on the highest point of the tower. A member of the United States Geological Survey has also made the ascent.

> determined by Captain Tuttle, the astronomer of the expedition, who calculated them from measurements with the sextant. The height of the summit above the river was found to be 1,126 feet, while approximately its elevation above the sea is 5,260 feet. The width of the summit from north to south is 376 feet, and the width at base is 796 feet. In an east-and-west direction the diameters are less.
>
> The rock * * * has a crystal-like structure on a grand scale, which from a short distance gives the column the appearance of a fascicle of gigantic fibers. From the base, which is considerably broader than the body of the peak, each fiber-like crystal or column rises in a bold curve to the bottom of the vertical obelisk, which it then follows to the summit. * * * The strata from which this igneous column springs are not in the least disturbed at the nearest points where they could be examined, about 50 or 75 feet from the base, but the sandstones * * * are converted into a compact white quartzite.
>
> *The Little Missouri Buttes* stand on the plateau of Dakota sandstone, about 4 miles west [northwest] of Bear Lodge and near the divide between the headwaters of the Little Missouri River and the Belle Fourche. They[1] * * * are said to be called by the Indians the "buttes which look at each other." Though prominent landmarks, they rise only between four and five hundred feet above their base. They are about one-half * * * of a mile distant from one another, but they are so thoroughly covered around their bases with débris that their intimate structure and relation could not well be determined. The Cretaceous sandstone forming the floor of the surrounding plain could not be ascertained to exhibit any disturbance or change of structure due to proximity to the igneous matter. Each peak has the same general conical form so often described, and a similar system of cleavage planes was also observed. Some cross planes give locally an appearance of columnar structure. The rock is a greenish-gray trachyte, similar to that of the Bear Lodge; but though it contains many crystals of feldspar, it is not so highly crystallized as the rock from the latter peak.[2] At the base of the Buttes in one or two localities a rock was found exceedingly light and cellular in structure, yellowish in color, and very like a volcanic tufa. As the result of a microscopic examination, Mr. Caswell designates it a rhyolitic breccia, including fragments of both sandstone and rhyolite.

Professor Russell's vivid description gives some idea of the solitary grandeur and beauty of the tower:[3]

> When Mato Teepee is seen from almost any locality in the valley of the Belle Fourche within a radius of several miles, one is not only forcibly impressed by the grandeur of the monumental form that dominates the landscape, but is delighted by the brilliant and varied colors of the rocks forming the sides of the valley and the immediate base of the tower. The Red Beds in the lower portion of the river bluffs show many variations of pink and Indian red, and have been sculptured into architectural forms of great beauty. The less brilliant Jurassic sandstones resting upon them and forming the upper portions of the bluffs, serve to carry the eye from the rich colors below to the dark forest of pines that grow above and to the still more somber precipices of the great tower which always appears in bold relief against the sky. * * *
>
> The shaft of the column is composed of clustered prisms which extend from base to summit without cross divisions. These prisms are usually pentagonal, although other forms are not uncommon. * * * Each prism tapers somewhat toward the

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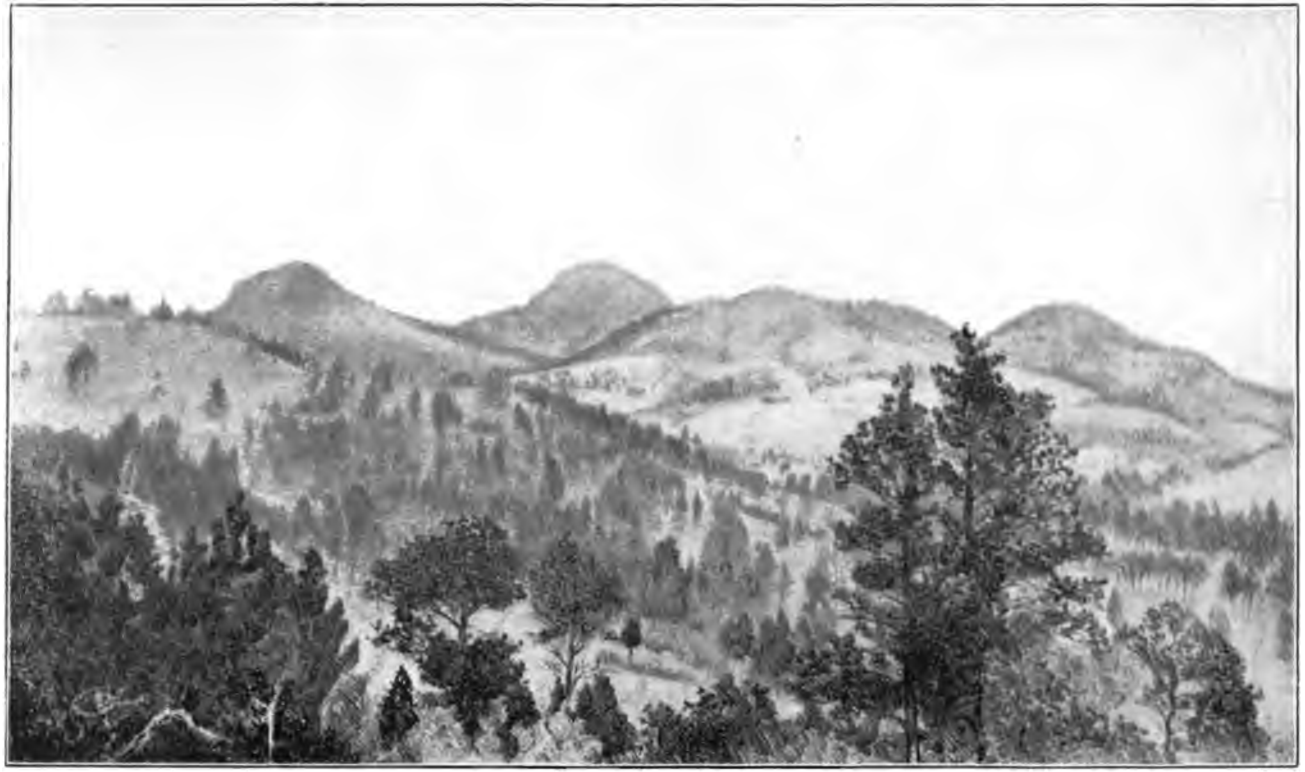
[1] Newton and Russell both describe Little Missouri Buttes as three in number, occupying angles of a triangle. There are four distinct hills, occupying corners of a quadrilateral.

[2] L. V. Pirsson (Am. Jour. Sci., Vol. XLVII, 1894, pp. 341-346) determined these rocks to be phonolite rich in soda feldspar.

[3] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, 1896, p. 32.



LITTLE MISSOURI BUTTES, FROM THE SOUTHEAST.

top, and near its upper extremity is cracked and discolored by weathering. At the base of the tower the columns in most instances, except at the southeast corner, curve abruptly outward, and at the same time increase somewhat in size. On the west side they become nearly horizontal. * * * Near the base of the tower, just above the treetops, the rock loses its columnar structure, becomes massive, and breaks with an irregular fracture. On the sides of the tower there are a few places where the lower portions of individual prisms have fallen away, leaving the upper 200 or 300 feet still in place. In such instances one has a good view of a section of the prisms, which are seen to be four, five, or six sided. Owing to the abrupt outward curvature of the columns at the west base of the tower, the fragments that have fallen from above have been thrown farthest out on that side and now form an extremely rugged talus in which fragments of huge columns lie piled in endless confusion one on another, suggesting the ruins of some mighty temple.

Northwest slope of Bearlodge Range.—When seen from a distance, along the road southwest of Warren Peaks, the Little Missouri Buttes are more prominent than Mato Teepee; they rise above the plains in a thronelike mass composed of four prominent dome-shaped hills (Pl. XXXVII), below which the tower sinks to comparative insignificance. The valley of Miller Creek on the northwest slopes of the Bearlodge Range is cut in Jurassic beds. Porphyry was encountered at one place on the road between Sundance and Mato Teepee, a fine-grained rhyolite occurring apparently as a sill. The most prominent outcrops on Miller Creek are mollusk and belemnite beds, a smoky fine-grained limestone, and a warm reddish wind-pitted sandstone, which forms prominent cliffs on the lower courses of the streams that drain the northwest flank of Bearlodge Range. The Little Missouri Buttes rest upon a platform of Lower Cretaceous sandstone, which forms a long terrace east of them, and this terrace stands at a considerable height above the base of Mato Teepee, which rests upon an oval platform of Jurassic shales, 3 to 4 miles to the southeast (fig. 95

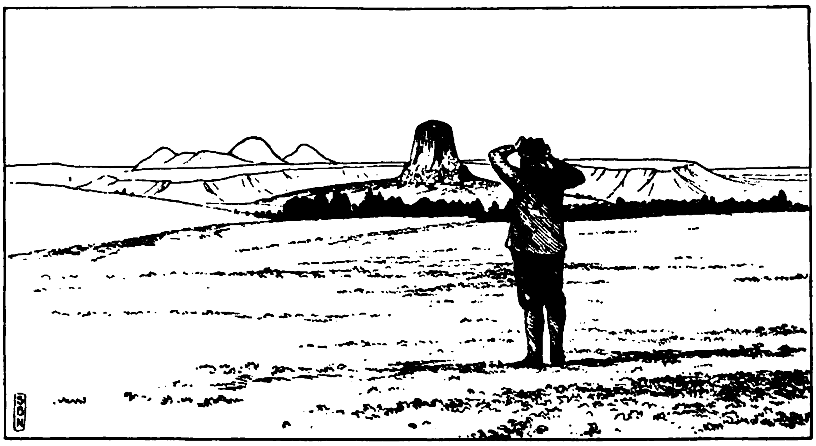
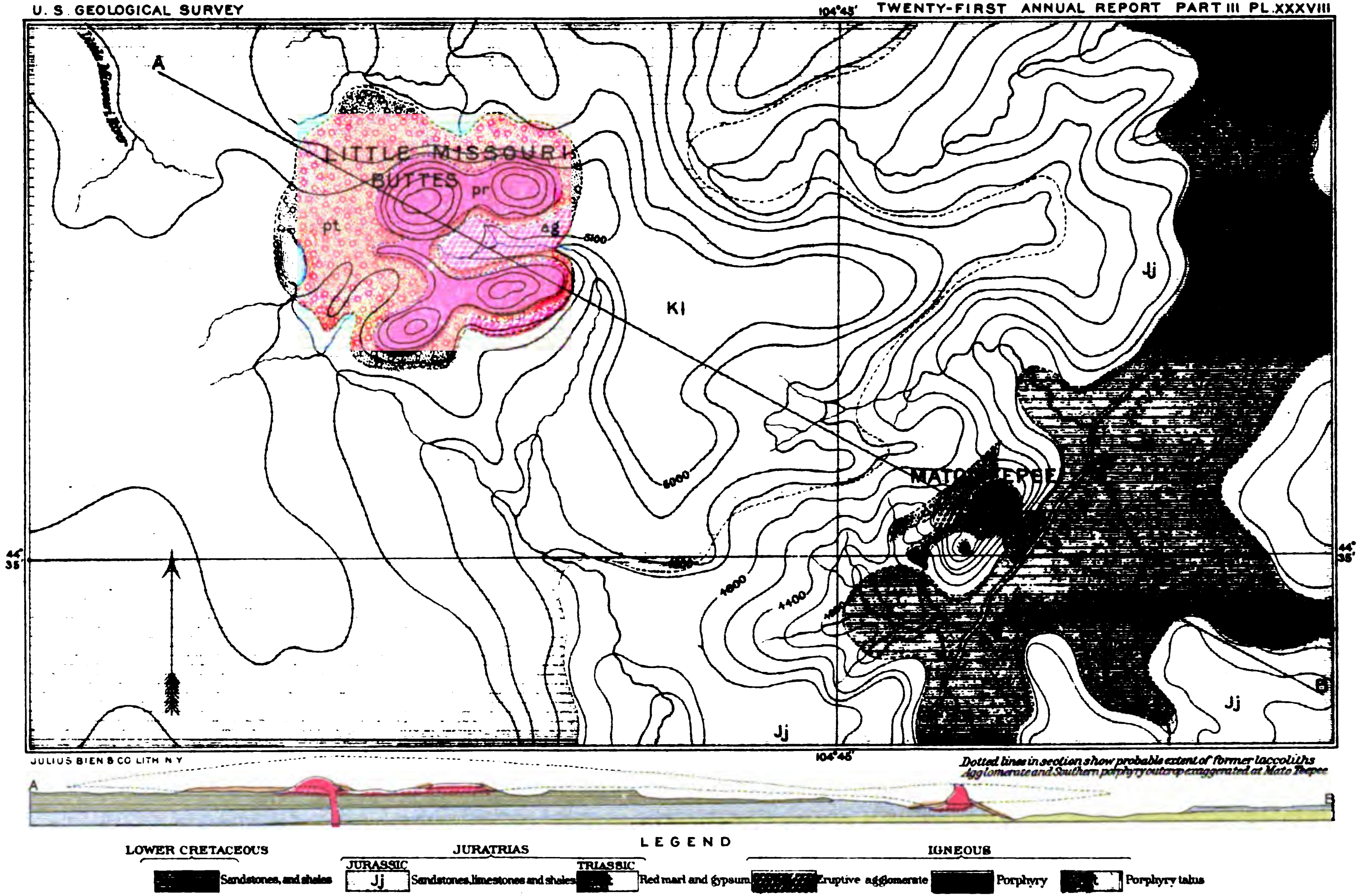


FIG. 95.—Mato Teepee and Little Missouri Buttes from the southeast.

and Pl. XXXVIII; see also Pl. XVIII). The northwestern slope of the Bearlodge Range is long and gentle, so that in looking up to the Warren Peaks from this side one would not suspect their height above the surrounding plains, so gradual is the slope. Seen from the east the Jurassic sandstone underlying Mato Teepee shows a distinct synclinal sag under the tower, dipping gently inward on either side of the mass of talus that forms a long slope down to the Belle Fourche bottom land (fig. 95).

LITTLE MISSOURI BUTTES.

The sediments between Mato Teepee and Little Missouri Buttes are in general horizontal, showing occasional aberrant dips due to the washing out, from beneath, of the soft red beds, and sometimes these dips vary widely in direction and amount within a distance of a hundred feet. The level bench of horizontal strata, conspicuous under the Little Missouri Buttes, is composed of white and buff sandstone of the Lower Cretaceous; and at the eastern foot of the northeastern butte, a hundred yards from the base, occurs yellow sandstone dipping gently west-southwest under a rounded hill slope covered with porphyry débris. In the gulch between this northeastern peak and the highest northwestern butte occurs a narrow spur consisting of red, weathered, porous, tuff-like material, much decomposed, carrying coarse fragments of pink granite, yellow-red sandstone, coarse Cambrian sandstone, and other rocks, in a vesicular matrix, of which but little is present in proportion to the quantity of inclusions. The rock resembles the breccias associated with the Deadwood and Terry porphyries (p. 187). The vesicles are largely decomposition cavities. Bowlders a foot or more in diameter, of granite or sandstone, occur scattered over the slopes in the basin area inclosed by the Little Missouri Buttes. From the summit of the highest peak Cretaceous strata may be seen on the north, northeast, southeast, and south, very near the porphyry. In all cases the bedding appears undisturbed by the eruptives, and has a slight westerly dip. The four buttes are all composed of porphyry. The rock on the summit is frequently fused at the edges of joint blocks to buff porcelaneous material, probably fulgurite produced by lightning. The Warren Peaks from this summit are more impressive than when seen from lower levels—culminating long slopes which rise gently on both sides. Far to the northward the snowy summits of the Bighorn Range may be descried. Granite fragments were included in the porphyry mass of the western butte, similar to those found in the breccia at the base of the buttes. The northeastern peak shows some columnar structure, with almost horizontal columns, the pentagonal column ends projecting from the face of the rock. There are also ledges trending north and south which stand out like dikes in the clefts of the rock mass, but they show no evidence of being litho-



GEOLOGICAL SKETCH MAP AND CROSS SECTION OF MATO TEEPEE AND LITTLE MISSOURI BUTTES, BLACK HILLS, WYOMING.

BY T. A. JAGGAR JR. 1900

Horizontal and vertical Scale

1 0 1 2 MILES

Contour interval 100 feet.

logically different. The spur extending southward from the foot of this peak is covered with rounded bowlders of coarse granite, trap, sandstone, and pegmatite, though none of these occur in the rocky talus above, at the foot of the porphyry wall; evidently the breccia lies under the porphyry.

The Little Missouri Buttes are four in number, the two northern ones being the highest and the most smoothly rounded in form. They are arranged at the corners of a quadrilateral, from one-half to three-quarters of a mile apart, and the porphyry is apparently continuous through the whole group except on the eastern side, where a stream has cut a canyon through it into the soft agglomerate that underlies it. This agglomerate occurs within the area of the Buttes on both sides of this stream and south of the southeastern butte. The talus slopes mark the contact between agglomerate and phonolite. Fifty feet above the gulch between the two eastern buttes occurs buff sandstone showing a dip of 7° directly under the northeastern butte, nearly due north. The same sandstone, practically horizontal, appears under the porphyry mass on the south side of the gulch. As the soft agglomerate occurs at the base of the several hills, especially in the central basin, it is probable that the presence of this deep-cut hollow in the midst of the hills is due to its less resistant character.

That the porphyry extended formerly over a much wider area than is now shown is proved by the presence of wide, flat accumulations of coarse porphyry fragments more than half a mile from the Buttes west and northwest. This creeping talus of weathered rock appears to have dammed one of the smaller streams on the southwest, and there a small pond is seen. The irregular coarse heaps of platy shingle with the pond in their midst resemble a moraine. A singular curved ridge extends from between the two southern buttes northwestward, consisting of igneous rock; below it, from a steep cliff at its western end, is seen a ridge trending northeast and southwest that resembles a dike. It is probable that this is one of the conduits which erosion is beginning to reveal beneath the porphyry.

The Little Missouri Buttes are encompassed by streams north, south, and west, which show traces of radiation and irregularly encircle the porphyry mass. The southern stream enters the Belle Fourche at an abnormal angle, forming with it a barbed junction. The Buttes reach their culmination in the northwestern peak, which was determined by the Newton survey to rise 5,563 feet above the sea. The northeastern hill comes next in height, while the southern ones are more elongate and lower. Probably the high northwestern peak bears the same relation to the others and to former peaks above the wide western talus that the central point of Custer Peak and the Woodville Hills bear to their outliers (see pp. 274, 277).

MATO TEEPEE.

Drainage.—Mato Teepee, on careful examination, exhibits many laccolithic characters, while in detail it shows close geologic relationship to Little Missouri Buttes. A stream encircles the tower on the north, taking its rise in a basin under the Lower Cretaceous bench. A similar stream encircles the southern end of the Jurassic platform, the divide between the two streams being a gently sloping sinuous ridge that extends to the foot of the Little Missouri bench. This bench, with the spurs that run out from it northeast and south, is

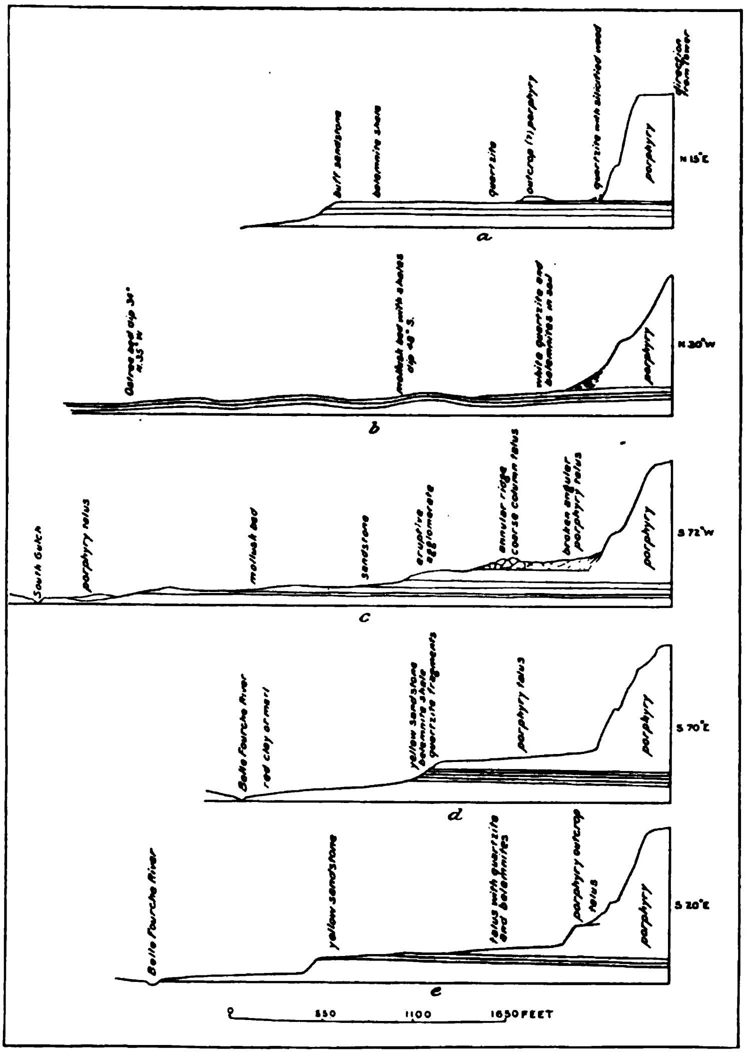


FIG. 96.—Radial cross sections from Mato Teepee.

singularly symmetrical (as shown on the map and in fig. 95) in the way in which it forms a semicircle about Mato Teepee as a center. To the east of the tower the Belle Fourche trunk stream has moved, probably by monoclinal shifting, down the gentle west dip of the soft Red Beds directly to the base of the tower, and its action is undercutting the Jurassic platform in a straight line parallel to the strike of the Mesozoic beds as a whole.

Stratigraphy.—Mato Teepee is underlain by Jurassic beds stratigraphically and topographically lower than those on which the Little Missouri Buttes rest. The latter loom to the westward high above the tower, resting upon the Lower Cretaceous sandstones which form the long horseshoe bench, the top of which is on a level with a point not far below the top of the tower.

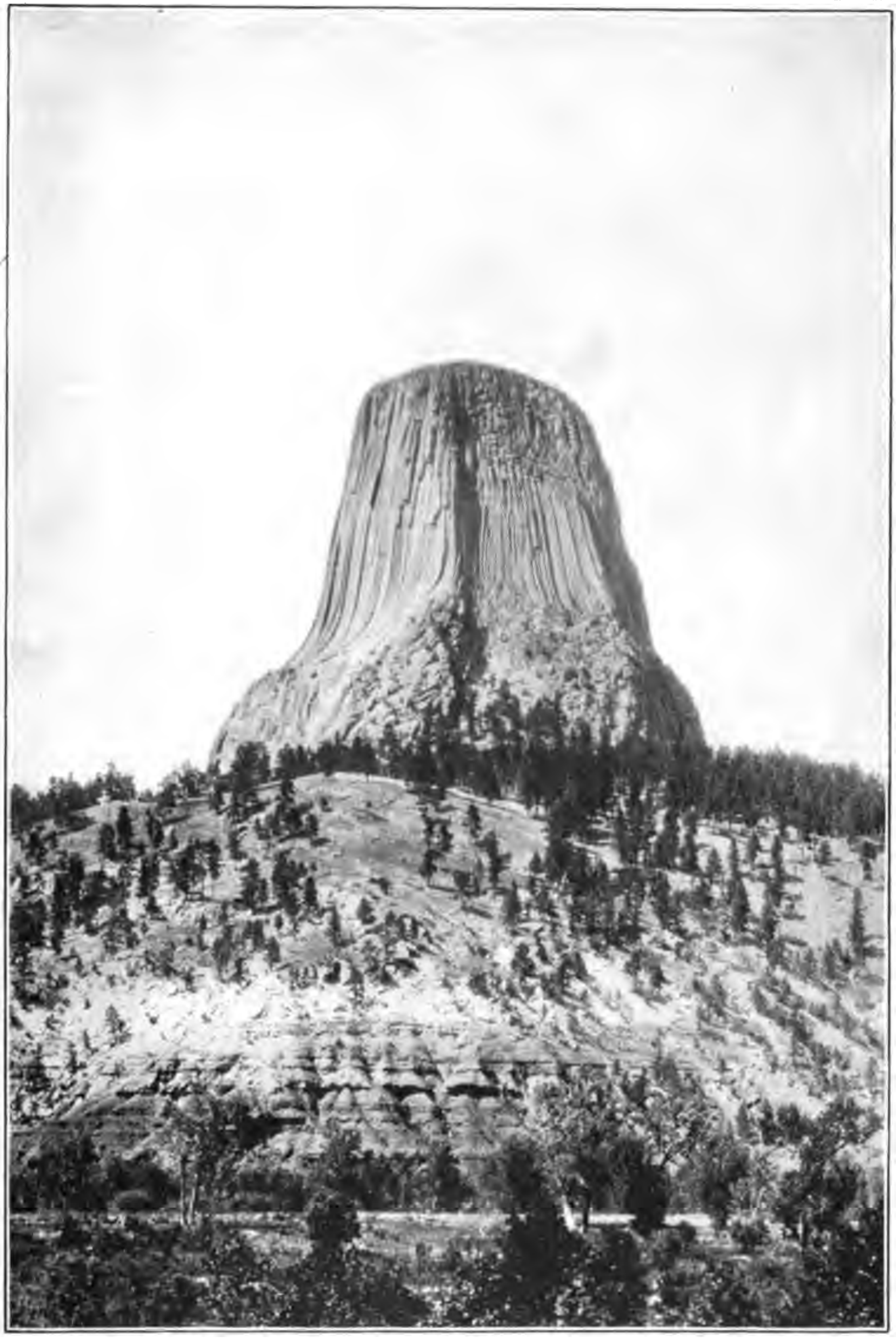
A hundred yards northwest of the tower, following the narrow divide between the encircling streams, a white fine-grained quartzite outcrops in the characteristic greenish soil of belemnite shale (fig. 96). A hundred yards farther west along the divide a shell bed (*Tancredia*) occurs, carrying concretions and dipping due south about 48°. Above and below are green shales, and the strike of the outcrop seems to curve. A little farther west oyster beds appear, dipping 34°, N. 35° W.; but these beds followed west along the strike become more nearly horizontal under the Little Missouri bench of horizontal strata. At the foot of this bench are green and purple clays capped by buff sandstone. A section up the slope shows progressively green shales, oyster beds, red clays, a second green shale bed carrying many large belemnites, and then thick buff sandstone of slight northerly dip. The greater part of the bench is made up of white and buff Lower Cretaceous sandstones. The oyster beds mentioned may be followed along the base of the cliff, showing dips varying from NNW. at a very high angle (45°) to SW., NW., SE., all in a distance of a few hundred feet. Such variations are entirely localized and independent of the general structure of the Jurassic strata of the region, and the most careful examination of the localities where these aberrant dips were found failed to show any evidence of disturbing igneous intrusions or other sources of violent deformation. It is believed that these dips are induced locally by erosion, the soft red beds being washed out from beneath in the adjacent gulches.

The accompanying sections (fig. 96) show the structure of the platform beneath Mato Teepee, which in general consists of level-bedded Jurassic sandstone, marls, shale, and quartzite; any variations from horizontality being rather of the nature of dip toward the tower than away from it (Pl. XXVIII). This again is probably due to the great weight of the tower pressing down the beds and squeezing out the soft red clays that have been exposed by erosion in the encircling valleys. N. 25° W. from the tower about 1,000 yards occur two quartzite ridges showing scattered fragments of quartzite on the side toward the tower, but without sufficient outcrop to give clear evidence of dip. About the same distance N. 55° W. in the gulch the buff standstone appears, dipping 2° due north. Two hundred yards due north of the tower there is an outcrop of quartzite very fine in texture, so as to appear almost like flint, of gray color, with a vertical lamination trending east and west, and 25 yards nearer the tower adjacent to the quartzite occurs a large mass of porphyry that appears to be an outcrop. On a small knoll N. 75° E. of the tower, only 30 yards from the porphyry talus, directly at the foot of the great basal bench, there is an outcrop of quartzite carrying fossil fragments of silicified wood, and this quartzite is abundant here in the tangled roots of fallen trees, indicating that this bed is the uppermost member of the Jurassic strata that underlie the eruptive mass. If there were any upturning about a vent there would be lower beds exposed here. This quartzite undoubtedly occurs higher than the belemnite shales that cover the ridge on the southern side of the tower. The quartzite varies, in places consisting of distinct clastic grains, and elsewhere being of fine-grained aphanitic texture. The platform bench northeast of the tower is not so long as on the southwest side. It extends northwest for some 2,000 yards, and the greenish belemnite shales here crop out below the quartzite. In a large ant-hill composed of coarse grit were found many small fragments of young belemnites. The best point of view for observing the synclinal sag, under the tower, of the buff Jurassic sandstone that is the principal cliff maker in the bench is the road near Ryan's ranch, on the eastern side of the Belle Fourche Valley. From this point the great talus of porphyry fragments that extends from the tower to the very border of the stream may be best observed, and on either side the sandstone is seen to dip inward gently, forming a V-shaped sag of wide angle in which the apex is immediately below the great columns.

The Jurassic section is approximately as follows, from the tower down:

Quartzite.
Tancredia limestone.
Smoky, fine-grained limestone.
Belemnite shales.
Oyster bed.
Bluff of tender buff sandstone (sometimes pink).
Green shales.
Thick shell bed, forming a hard band.
Buff marl.
Gypsiferous red beds (marl).

Structure of the tower.—The tower is sharply divided at a point more than a third of the distance from base to summit by a line that marks the beginning of the columns and a bench formed by the upper



MATO TEEPEE, FROM THE SOUTH, SHOWING HORIZONTAL JURASSIC STRATA BELOW.

limit of the massive uncolumnar base. This massive lower portion is jointed variously, showing sometimes a flat, vertical, rough lamellar parting and in other places irregular joints (Pl. XL). It contains not a trace of the perfect columnar habit of the upper portion, which is seen, however, to merge into the lower portion locally where the columns curve out and are lost in the massive bench. On the SSW. corner the basal mass rises to a height of from 40 to 50 feet above the talus, and a narrow columnar band resembling a dike extends downward and outward into the base from the curved lower portion of the upper columns. This band is about 40 feet wide. Seen from this side the upper columns slope back about 4° or 5° from the vertical on the western side of the tower and 10° to 12° on the eastern side. On the southwest face of the tower the columns make a curve outward, of long radius in a western direction at the base, ending in a horizontal position at the bench that marks the top of the massive base. This base or pedestal extends all around the tower and is nowhere entirely concealed under débris. The columns are marked horizontally by faint ridges or swellings that give to the rock locally an appearance that resembles bedding. This is most marked in the upper quarter, where there are a number of overhanging columnar masses left without support below because the straight and upright lower portions have fallen out, leaving clinging remnants above. The upper part is cross jointed and irregularly cracked, as though more weathered. The whole mass has a yellowish-green color, produced by lichens. The summit is flat above and slopes gently on the eastern side, falling off at a sharp angle on the extreme east corner and becoming vertical below. The western face is a vertical columnar cliff to the highest summit. Many of the columns appear in places to be large hexagonal or octagonal masses above, but where broken away below a single column becomes divided into a double or triple fluting that resembles a gothic pillar composed of independent pentagonal pieces. Many of the columns unite above to a single larger column, in groups of two or three, precisely like solidified columnar starch. On the south side the columns diverge downward east and west, with straight medial members (Pl. XXXIX). The base of the eastern curving columns is here overlapped by massive shells or laminæ.

Single columns found scattered in heaps about the outer margin of the talus at the base of the tower average 6 feet in diameter and have pentagonal or weathered roundish cross section. In one place a single column, resting in its niche on the tower's face, was seen to be divided into five separate blocks, like a masonry pillar, and this was supported below by a half column, split longitudinally, occupying a downward continuation of the same niche. In another case seven columns, together in a bunch, had fallen away below, but were still clinging above. The rock that forms the massive base was carefully examined at many points in comparison with the rock of the fallen columnar fragments, and no positive difference in texture could be seen. The rock was carefully examined for inclusions, and some basic aggregates, large broken feldspar masses, and a substance resembling diorite were found embedded in the coarse porphyry, but no granite or other rocks characteristic of the agglomerate were found in the Mato Teepee porphyry, though large granite fragments are quite abundant in the porphyry of the greater peak of Little Missouri Buttes.

Mato Teepee agglomerate.—At the foot of the tower on the WSW. side, immediately below the main talus and encircled by porphyry talus slides, is a small rounded grassy hill strewn with rounded subangular or irregular fragments of granite, limestone, Jurassic sandstone, Cambrian quartzite and glauconitic sandstone, purplish rhyolite, a little slate or schist, black shales of two varieties, flint, and coarse pegmatite. This extraordinary accumulation of fragments was found to be an agglomerate similar to the one that underlies the porphyry of the Little Missouri Buttes. It here outcrops only in this small elliptical spur or hill, about 150 yards in length, trending S. 72° W. from the tower, and completely surrounded by bowlder slides of talus material that unite below the foot of the agglomerate hill and extend down the gulch into the valley. How much more of this agglomerate may be present under the talus it is impossible to say; but it is significant that on the opposite side of the tower the Jurassic quartzite is found to within a stone's throw of the foot of the steep talus, and no trace of the agglomerate occurs, nor was this agglomerate found anywhere else about the tower. A trench was excavated in the hill in order to obtain specimens of all the fragments and of the matrix, the last appearing to be a decomposed porphyry. The most conspicuous fragments of the agglomerate are granite, in either rounded or angular forms, varying in size from small pebbles to bowlders 1 or 2 feet in diameter. The rounded fragments have a somewhat faceted character, unlike the smooth polish of stream-rolled material. A limestone bowlder of characteristic Carboniferous habit, containing spirifers and other fossils, about a foot in diameter, was found to be encased in a shell half an inch thick, which could be broken away, parting smoothly from the rounded surface beneath, as though the mass had been subjected to calcination by heat. Except for the greater variety of contained fragments, this agglomerate is essentially like the one found in the Little Missouri Buttes and those of the eastern laccoliths. Excursions were made over sections through the platform in directions radial to the tower as a center, south, southwest, west, northwest, northeast, east, and southeast, and also completely around the foot of the tower and up to the top of the massive pedestal in two places, without discovering any other outcrop of the agglomerate. Some of the sandstone formations represented in the agglomerate have a crust in which no individual sand grains can be seen, and this appears to be the product of fusion. West and northwest of the agglomerate hill Jurassic strata, showing horizontal bedding, outcrop in the gulch, and apparently lie directly beneath the weathered agglomerate.

On the southern end of the platform a hundred yards from the base of the tower there is a wide, flat, rounded porphyry knoll, exposing some 30 to 40 feet of surface that appears to be an outcrop in place. S. 35° E. from the tower, at a distance of 30 feet, there is a faint swell or ridge in the talus, and an exposure of massive porphyry forming a steep cliff. This also shows every evidence of being in place. The faint elevation here observed in the accumulated jumble of bowlders at the tower's base seems to be a persistent character on all sides, the fragments forming an ill-defined annular ridge, separated from the wall talus at the base of the tower by a faint depression 20 to 30 yards in width. It is probable that this ridge has been produced by the rebound of large fragments striking the pedestal or the wall talus and being forced outward so as to fall in a ring away from the immediate base of the mass. It is noticeable that the fragments of columnar material are more abundant in this outer ridge, while the inner talus is composed of flakes from the pedestal and smaller blocks of irregular form. This is to be expected, as the huge columns falling from a height and meeting obstruction in the projecting pedestal necessarily must bound or roll away for some distance (Pl. XL). It must not be imagined, however, that this arrangement is in any sense symmetrical or even striking, for the jumble of bowlders is in many places confused and entirely disorderly.

The Mato Teepee agglomerate contains in abundance two varieties of carbonaceous shales, the one breaking in small rectangular blocks of dark gray color, the other in soft, flat, coaly laminæ. Such shales are not known to the writer below the Lower Cretaceous and Benton, terranes which are *stratigraphically higher than the present location of the breccia*. This is very strong evidence in favor of the Mato Teepee intrusion being an offshoot from the Little Missouri Buttes, for the latter were probably intruded in Benton carbonaceous shales. The identity of the Little Missouri and Mato Teepee breccias is unquestionable; they contain the same kinds of fragments, and their matrices are not essentially different. The matrix of the Mato Teepee breccia is too soft for slicing; the powder under the microscope resembles a granite arkose, and granitic material is most abundant among the coarser fragments. This granite, brought up from the depths, is either Archean or an intrusive in the Algonkian. It is different from the Nigger Hill or Harney granites, and resembles rather the Archean granites of the Rocky Mountains. The powder carries much kaolin, quartz grains, brown mica, and occasional transparent feldspar flakes. The quartz grains are broken or have a faceted surface, suggesting corrosion.

Little Missouri agglomerate.—The Little Missouri agglomerate is sufficiently hard for thin slicing. The microscopic section shows small angular fragments, reaching a maximum of 1 to 2 millimeters in diameter, of quartz, orthoclase, microcline, pieces of fine-grained porphyry with ægirine, magnetite, and calcite, in an earthy brown groundmass. The groundmass, when examined under a high power, is seen to consist of a nearly isotropic base with specks of brown iron oxide. Here and there transparent portions of the base show a faint felty polarization. Ferromagnesian constituents in general are not preserved; there are one or two doubtful cases that may be idiomorphic outlines of an original hornblende or augite crystal, preserved by paramorphic masses of calcite. The thin section shows no evidence of true vesicular structure. The hand specimen is very porous, but this is due to the dissolving out by weathering of carbonates, etc., from pseudo-amygdules, probably largely marking the loci of former bisilicates.

Evidences for laccolithic origin of Mato Teepee.—It is probable that these breccias were the first and most fluid injections of a magma which rose rapidly and with some violence through fractures from Algonkian to Cretaceous. The conduits were dikes now nearly concealed under the Little Missouri Buttes. The laccolith spread southeastward in Benton shale, met an opposing northwest dip off the Warren Peak flanks, broke downward through the Lower Cretaceous sandstone, and formed a subordinate Mato Teepee laccolith in soft Jurassic strata.[1]

Seen from the valley of the Belle Fourche, at the base of the tower on the south (Pl. XXXIX), the Jurassic strata beneath the tower appear absolutely horizontal. These strata are massive buff sandstone above, and clays, marls, and limestones below. The columns from this point of view show best their tendency to flare outward. As this flaring is symmetric rather to a point within the tower than to an axial direction, it is probable that the tower represents nearly the center of the original lens.

The massive base bears the same relation to the columns as the medial portion of the dikes figured in Pl. XXXIII. Were it exactly the equivalent of the dike, we should expect other columns below, the massive portion being in the middle. It is probable that the presence of a muddy breccia as a lowest stratum for the laccolith interfered with the development of basal columns, and probably also the action of gravitation makes the contraction expend itself less symmetrically in a horizontal lens than in an upright dike. The present upper surface of Mato Teepee is smooth and possibly represents nearly the actual upper contact, from which the shales have been weathered away.

The geologic section (Pl. XXXVIII) shows an ideal reconstruction

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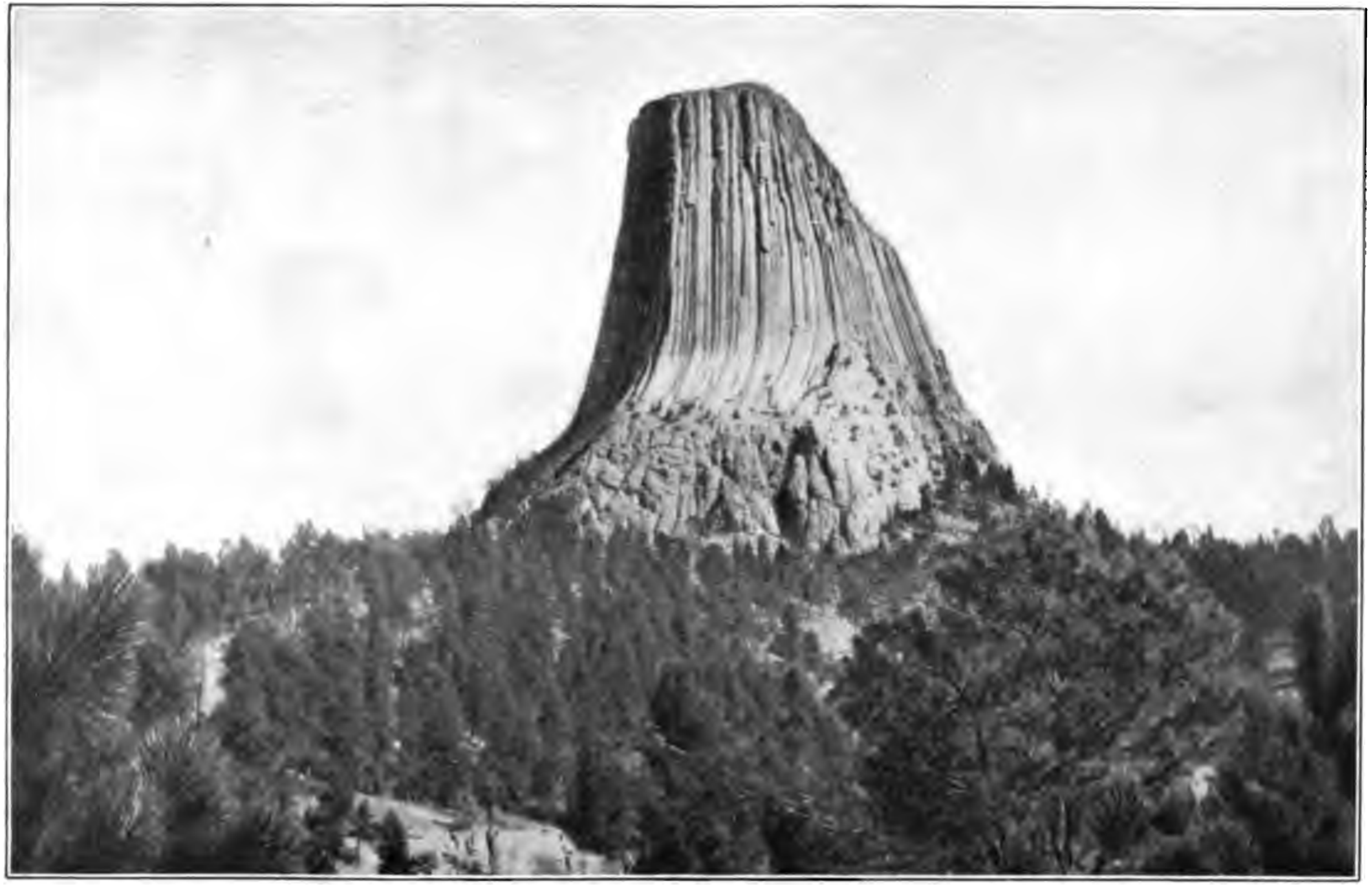
[1] Judd has figured a sill of basalt in Skye, which breaks downward across strata after spreading along a higher horizon. Volcanoes: Internat. Sci. Series, Appleton, 1881, fig. 56.



MATO TEEPEE, FROM SOUTHWEST END OF JURASSIC PLATFORM.

of the original laccolithic masses. Mato Teepee was simply a sill or subordinate lens from the Little Missouri Buttes laccolith. The encircling drainage favors the hypothesis that the Mato Teepee mass was lenticular, so that streams became adjusted about the peripheral slopes. Possibly the conduits of Little Missouri Buttes were inclined to the east from the vertical, so as to inject the magma in the direction of Mato Teepee. The injection was thus eastward, toward Warren Peaks—i. e., in the same direction as those which formed the Sundance Hills, on the opposite side of the Bearlodge Range. Injected southeast through beds gently dipping away from Warren Peaks, the spreading igneous rock, as usual, truncated bedding planes obliquely, so that the first injections charged with brecciated material reached the Mato Teepee region at a horizon lower than that of the conduit. The soft breccia probably had its greatest development in the region between Mato Teepee and the Little Missouri Buttes, hence those portions of the laccolithic mass occupying this intermediate region were the first to be eroded away. The presence of this undermining breccia accounts for the steep walls of Mato Teepee and Little Missouri Buttes. It is probable that the persistence of Mato Teepee at all is due to the fact that it represents the most perfectly columnar portion of the original laccolith, and the spread of the columns at the base is architecturally necessary for the maintenance of the shaft. The tower may thus be considered a geological case of "survival of the fittest."

The proofs that Little Missouri Buttes were the main laccolith of which Mato Teepee was a subordinate offshoot, may be summarized as follows: The Little Missouri Buttes form the larger mass today, encircled by the larger streams, and show evidence of conduits beneath in the shape of dike ridges, a large mass of breccia at the base, irregular and horizontal columns, and inclusions of granite in porphyry. Mato Teepee shows evidence of smaller size and lenticular form in the arrangement of the smaller encircling streams, and shows only a little of the breccia at the base, and that on the side of the Little Missouri Buttes; the breccia contains fragments of black shale from the Little Missouri Buttes horizon; the vertical columns give evidence of an extended horizontal upper cooling surface, and the Jurassic beds below give evidence of a horizontal basement; flat porphyry outcrops on the Jurassic platform give evidence of former greater horizontal extension of the Mato Teepee porphyry; entire absence of dikes or deformed sediments indicates that the porphyry came into its present position through lateral conduits from the greater mass.

Other hypotheses.—There are three other hypotheses for the origin of Mato Teepee that should be tested: (1) May the conduit be in the slopes of the Bearlodge Range to the southeast? (2) May these eruptives be extrusive lavas? (3) May the conduit lie beneath the tower? With regard to the first possibility, the slopes of the Bearlodge Range were crossed in two directions by the writer and no trace of igneous rock of the Mato Teepee type was found. There are undoubtedly sills in Jurassic strata far up the slopes, near the Warren Peaks, but the rock shows no resemblance to that of Mato Teepee, and the distance is at least 10 miles. The same strata recur between, without intrusions. The second alternative may be quickly dismissed as unworthy of serious consideration. The only feature resembling an extrusive lava is the Little Missouri breccia. Similar porous breccias occur in twenty places in the Deadwood and Terry districts associated with unquestionable intrusives. The rock of Mato Teepee is similar to many phonolites in the Terry district that were unquestionably pre-Oligocene, and if the Mato Teepee laccolith was contemporaneous with them it was covered by at least 4,000 feet of strata at the time of its injection. The evidence from physiography, from petrography, and from geology points to intrusive origin. The third question has been answered in the last paragraph; the most conclusive evidences against a subjacent conduit to the Mato Teepee mass are the presence of black shales in the agglomerate, the undisturbed horizontal beds which the tower rests upon, and the vertical columns.

CHAPTER III.

PHYSIOGRAPHIC FORM OF ERODED DOMES.

There are few localities where the consistency of individual strata so obviously produces characteristic erosion forms as in the Black Hills. Attention has been called to the characteristic benches or taluses, escarpments or valleys, that belong to each formation. Hard rocks make the mountains; soft rocks make the valleys; the great plains, relatively a lowland, are composed of very gently dipping soft rocks. In order to trace out the history of present-day topographic forms produced by laccolithic intrusions, the important geologic features to be considered are distribution of hard and soft strata, their thickness above the eruptives at the time of intrusion, the effect of that intrusion on the initial surface, and the relation of intrusion to the greater uplift that initiated or modified the greater drainage.

DISTRIBUTION OF HARD AND SOFT STRATA.

Distribution of hard and soft strata in vertical column (fig. 60 and Pl. XIX) has already been discussed in connection with the selective action of intrusive magmas, which spread most easily along the shales. The members "competent" to resist deformation are equally competent to resist erosion. The porphyry itself is perhaps most resistant; next, the great limestone; third, the Permian limestone (Minnekahta), a wonderfully persistent scarp maker, despite its thinness. Both the Minnelusa and Jura-Cretaceous formations make hills and ridges, and Niobrara limestone forms conspicuous buttes above the soft shales of the plains.

Between the hard members occur soft, erodible shales which progressively increase in thickness upward concomitantly with a similar decrease in the hard beds. Above the Cambrian shale horizon of intrusion there are in general three strong, hard members and three soft. The hard ones are the Siluro-Carboniferous (900 to 1,500 feet), Jura-Dakota (600 to 1,000 feet), and Niobrara (500 feet); the soft members are the Permo-Trias (300 to 400 feet), Benton (500 to 800 feet), and Pierre (2,000 feet), and above are incoherent Upper Cretaceous and Laramie beds.

The thickness of strata above the intrusives (p. 185) may have been between 5,000 and 8,000 feet, if the intrusion took place in Eocene time, and it has been shown that geologic evidence favors uplift of the

Black Hills at the same time. Some deformation by folding took place, and this was complicated by the porphyries into what may be aptly called pustular deformation, to use Newton's word, without, however, implying superficial action. The igneous bodies were separated by interdome synclines with axes, in many cases, trending radial to the greater Black Hills uplift.

UPWARD ABSORPTION OF DOME FLEXURE.

From the elongate oval or elliptical dome of the Black Hills that extended for more than 100 miles, warping up Cretaceous and perhaps early Tertiary strata, streams poured down the slopes and flowed away to the sea, from the moment the arch was exposed to rainfall. Such streams had courses radial to the uplift, consequent upon the initial slopes. If there was no actual initiation of drainage, and the uplift went on pari passu with the erosive action of an already existent river system, the evidence from the present drainage shows nothing to prove it. The most conspicuous features of the greater streams at the present time are their avoidance of the uplift and their deflection around it north and south, the radial courses of the streams which rise within the uplifted area, and the deeper erosion, into the flanks of the dome, of the eastern streams—i. e., streams of greatest fall from source to junction with the Platte and Cheyenne rivers. To what extent were the first consequent streams influenced by dome-shaped masses of intrusive rock in strata 6,000 feet below them?

In diagrammatic reconstruction of domed strata the beds are usually represented as maintaining uniform thickness around the bends.[1] The same rule is frequently followed in representations of folded strata. It will readily be seen that such construction entails radial enlargement of a fold transmitted from a thin stratum below to a thick one above; logically, with such construction, the upper stratum will have greater dip length than the lower one, and is so represented. In other words, a small curve in the depths can be constructed to transmit a great curvature to the surface a thousand feet above. Certainly such a construction has no foundation in observed fact. In miniature and on a large scale folds diminish in size upward by lateral absorption of motion. Willis has shown that the transmission and size of a fold are dependent on the rigidity and thickness of strata involved. Massive limestones under load bend; thin-bedded shales flow, fault, and crumple. Shales involved in and above a dome of limestones pushed up from below become stretched and thinned on the arch, while they thicken and crumple in the sag. In soft clays there is probably a certain amount of squeezing flow. Evidence that such thinning of clays over laccolithic arches actually took place is abundantly shown in the crushed Red Beds on the flanks of Elkhorn, Crook Mountain, Crow Peak, and Bear Butte. The result of such failure of soft beds to transmit doming is a gradual dying out of the dome upward (figs. 75 and 98), in the same way that a monoclinal or anticlinal fold or a fault may die out. The rapidity of absorption will depend upon the softness of upper beds; as the Black Hills section becomes progressively softer upward the conditions are the more favorable for absorption of flexure in small vertical distances.

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[1] Geology of the Henry Mountains, by G. K. Gilbert, 1880; frontispiece, figs. 8, 9, 18, 73.

Cross sections showing Mount Holmes bysmalith, by J. P. Iddings: Mon. U. S. Geol. Survey, Vol. XXXII, Part II, Pl. V; Jour. Geol., Vol. VI, 1898.

Contrast with these Hesperus Mountain and La Plata Mountains, W. H. Holmes: Hayden Survey, 1875, Pl. XLV, opposite page 271. Holmes clearly perceived the tendency of domical curvature to diminish upward.

The manner in which doming dies out, and the relative distribution of hard and soft beds, is shown in fig. 98 (p. 277). There is some direct field evidence of absorption of dome flexure. Rapid diminution in dip of flanking beds upward on the side of a laccolith shows within a few hundred feet of strata a diminution in curvature. This is clearly shown on the south side of Crow Peak, the west side of Kirk Hill, and east of Bear Butte (figs. 83 and 93, Pl. XXX). Such diminution in dip is conspicuous in laccoliths having most intense dome flexure.[1] Another evidence is presented by Circus Flats; the outcrop affected by the subterranean dome is hardly larger than Bear Butte (Pl. XXX). By analogy with other subordinate laccoliths, Bear Butte is much smaller than the underground main laccolith of which it is an offshoot. The Circus Flats ellipse in Benton shale has probably not more than half the diameter of the laccolith beneath. Lastly, miniature domes and lenses in Cambrian shale (figs. 65, 66, 67) show absorption of the flexure which they cause, a few feet above, and similar effects are produced by laboratory experiment (Pl. XLIII).

EROSION STAGES REPRESENTED IN THE BLACK HILLS.

Attention has been drawn to the evidence by analogy shown in the several stages of erosion from covered dome to uncovered laccolith, that in part demonstrates the originally intrusive character of all of the younger porphyries of the Black Hills. Six cases have been selected (Pl. XLI) which illustrate the progressive denudation of the laccolith and the arrangement assumed by the drainage which throughout the several stages has served as transporting agent for disintegrated material. The six types are Elkhorn Mountain, Crook Mountain, Citadel Rock, Kirk Hill, Crow Peak, and Pillar Peak. Two others should be added to this list: Circus Flats (Pl. XXX) and Mato Teepee (Pl. XXXVIII).

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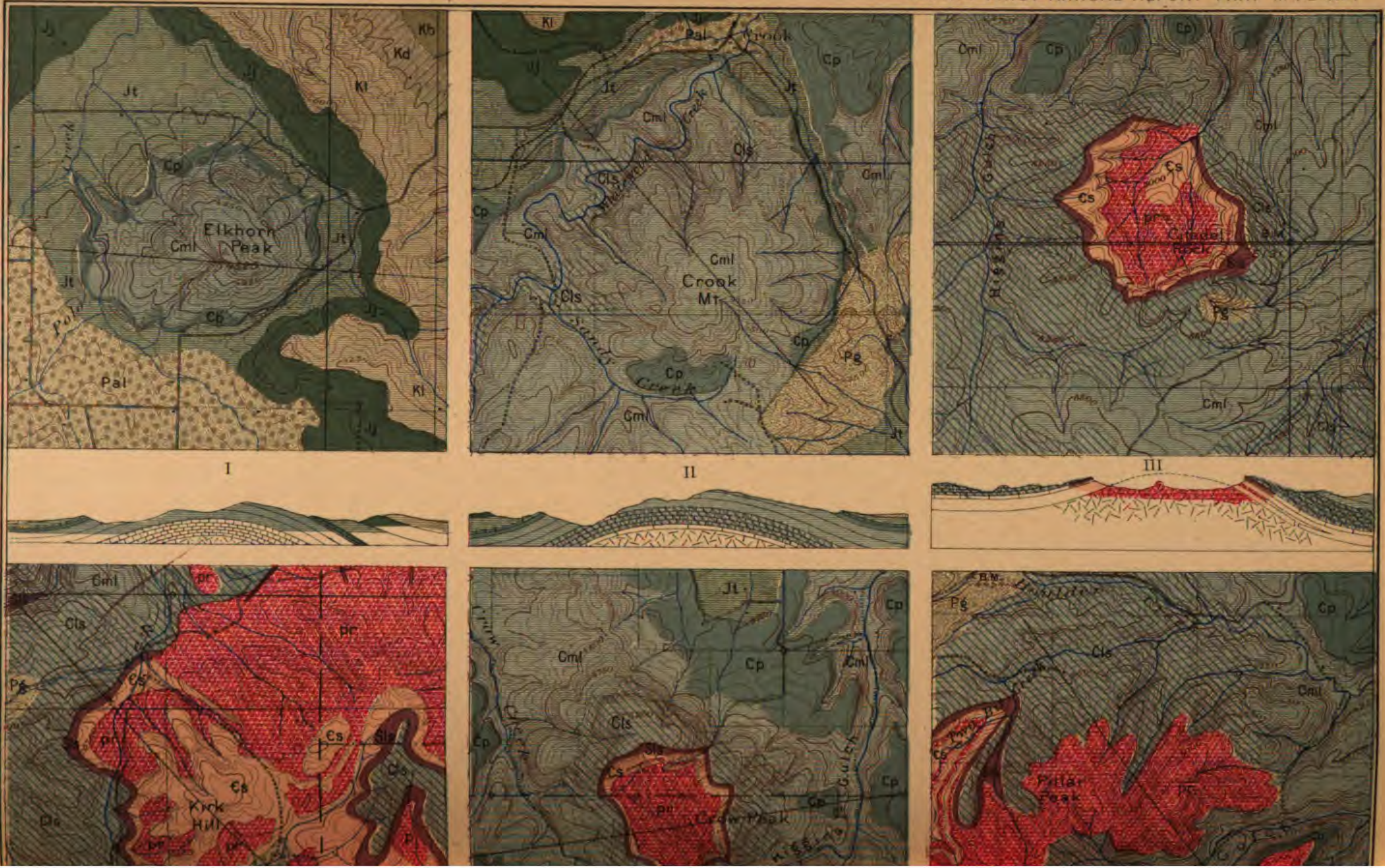
[1] Compare cross section of Mount Hillers, fig. 26 of Gilbert's Henry Mountains; also sections of Thunder Mountain, figs. 44 and 45 of Weed and Pirsson's Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, 1900, p. 365.

CIRCUS FLATS.

Circus Flats represents the earliest stage of laccolith erosion in the region of the Black Hills. The buried eruptive dome has deformed strata up to and including Benton Cretaceous. Small streams radial on the dome of Dakota sandstone have shifted until that northern stream, which has greatest fall to its junction with Spring Creek, has mastered the others and eroded out a hollow in the center of the dome on soft Triassic red marls (Pl. XXXII). Subsequent streams concentric to the dome follow annular valleys on soft beds, and the greater stream, Spring Creek, turns aside to encircle the dome on the east and north, following Benton shale and avoiding Dakota sandstone. The initial course of this greater stream was northeast, off the Black Hills uplift. The initiation of such drainage took place when the Black Hills were first subjected to atmospheric erosion. How such erosion came about is not known, whether from recession of an Eocene lake or by rainfall which continued while the uplift took place. That the streams flowed radial to the uplift is amply shown by their present distribution. The drainage features of Circus Flats may be summarized as follows: Deflection of a trunk stream superposed upon the dome through a thickness of several thousand feet, now eroded away; local development of radial branch streams on a hard stratum; local mastery by one of these streams within the area of the dome; development of concentric subsequent streams on soft strata: a hill has been converted into a basin surrounded by a horseshoe-shaped ridge, and drainage radial outward has become radial inward.

ELKHORN PEAK.

In Elkhorn Peak, higher on the flanks of the Black Hills, erosion has carried away the upper beds, and the soft Red Beds form here a valley around a hard Minnelusa sandstone dome which stands in relief. The sandstone dips away from the summit on all sides, and is incised by erosion most deeply on the southwestern side, but in no case is the underlying gray limestone exposed. Minnekahta limestone forms revet crags on the flanks, with steepest dip on the east and southeast. Above it the Red Beds have been closely compacted within a synclinal fold southeast, where a narrow valley separates Elkhorn Peak from hills of Jurassic and Cretaceous strata. On the northern, western, and southwestern sides Minnekahta limestone passes by gentle curvature under the broad Red Valley at Centennial Prairie. The drainage on the slopes of Elkhorn is chiefly radial, small gullies of subsequent development tending to follow the soft layers, producing in many cases a rectangular system. Larger streams, as in the case of almost all the laccolithic domes of this region, form an encircling valley about the base of the mountain in soft red Triassic marl. When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Crook Mt.
Sands Creek
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Citadel Peak
Higgins Gulch
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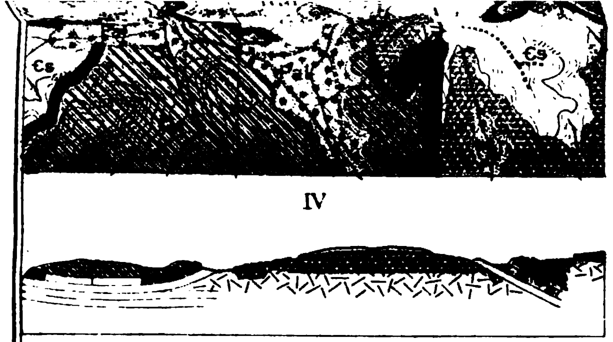
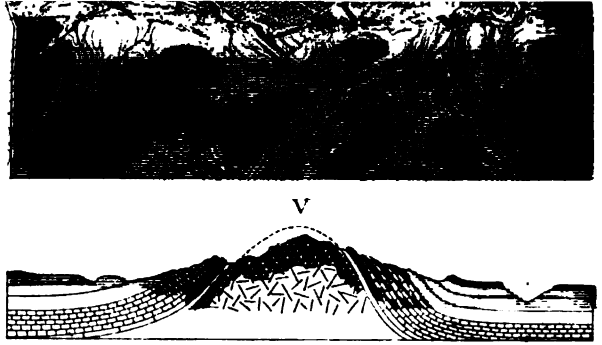
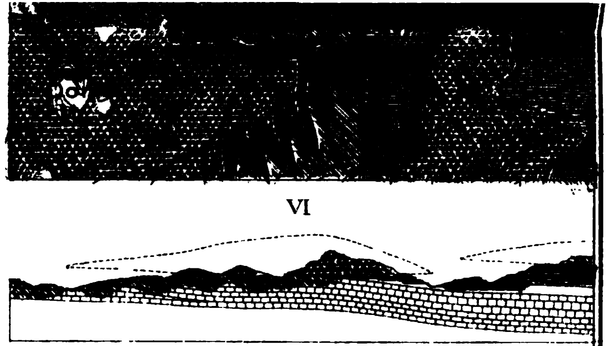
Crow Creek
Crow Peak
Higgins Gulch
Boulder Creek
Pillar Peak







LEGEND

PLEISTOCENE
- Pal — Meadow bottom land Alluvium
- Pg — Ancient stream gravels

CRETACEOUS
- ■ — Benton dark shales
- Kd — Dakota brown sandstone
- Kl — Lower Cretaceous sandstones and shales

JURATRIAS
- JURASSIC: ■ — Sandstones limestones and shales
- TRIASSIC: ■ — Thick red marls and gypsum

CARBONIFEROUS
- PERMIAN: ■ — Minnekahta thin limestone over red bed
- Cml — Minnelusa limestones and sandstones
- ▨ — Massive limestone

SILURIAN
- ■ — Arenaceous limestone

CAMBRIAN
- €s — Shales, limestones, and sandstone

IGNEOUS
- ▨ — Porphyry
- ╱ — Dikes

GEOLOGICAL MAPS AND CROSS-SECTIONS

ILLUSTRATING

STAGES IN EROSION OF LACCOLITHIC DOMES

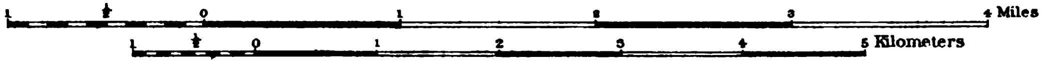
BLACK HILLS, SOUTH DAKOTA

BY

T. A. JAGGAR JR.

1900

Horizontal and vertical Scale

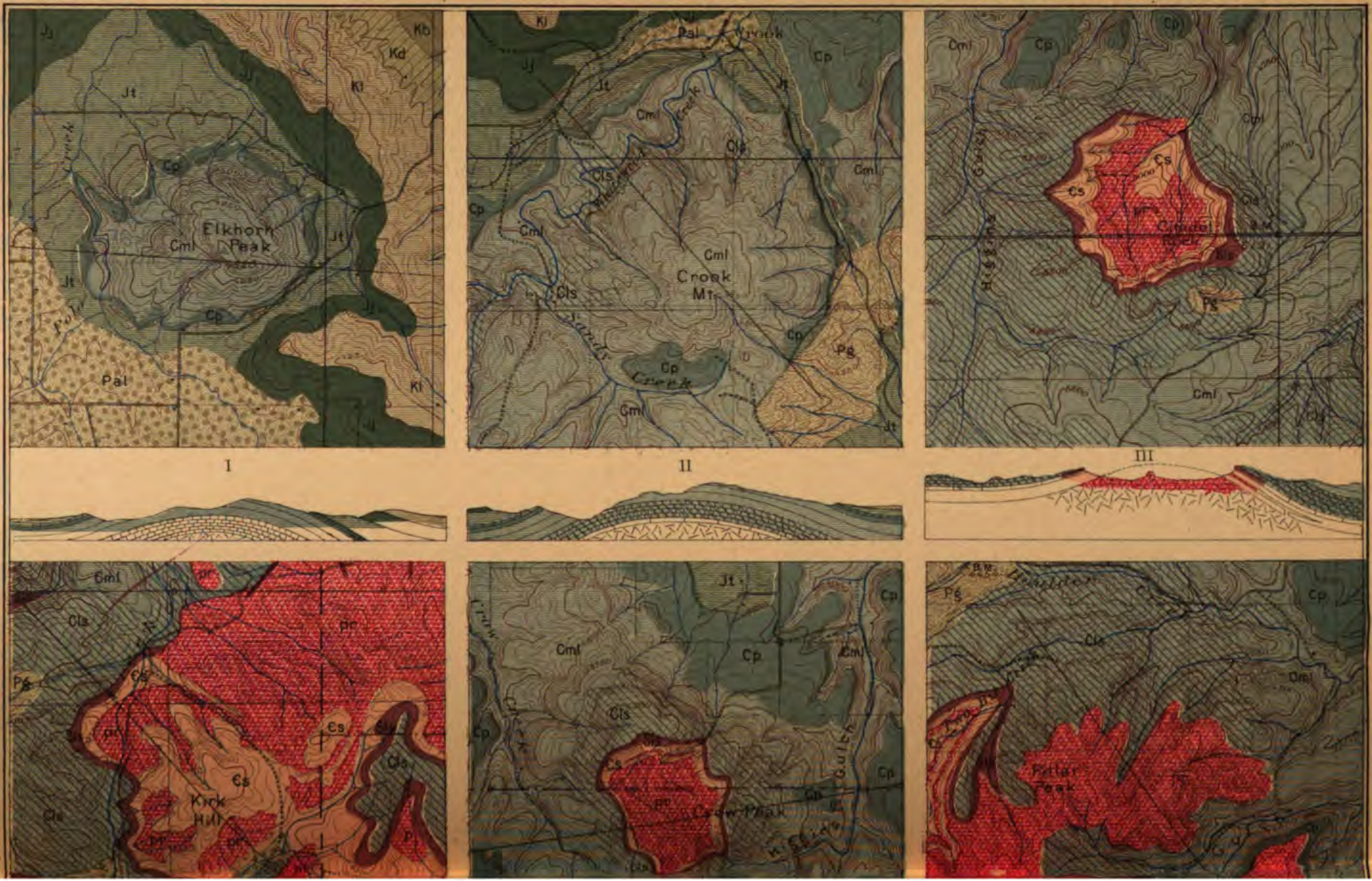


Contour interval 50 feet
Datum is mean sea level

Topography by W. H. Herron and Arthur Stiles

Colored portions of sections indicate rocks exposed

JULIUS BIEN & CO LITH N Y


Jj
Jt
Kl
Kd
Kb
Cp
Cml
Elkhorn Peak
Pal
Creek
Pole
I
Pal
Crook
Cls
Cp
Crook Mt.
Pg
Sandy Creek
Whitewood Creek
II
Cp
Cml
Cs
Citadel Rock
Higgins Gulch
Pg
III
Cml
Cls
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Cs
Kirk Hill
Crow Creek
Crow Peak
Gulch
Jt
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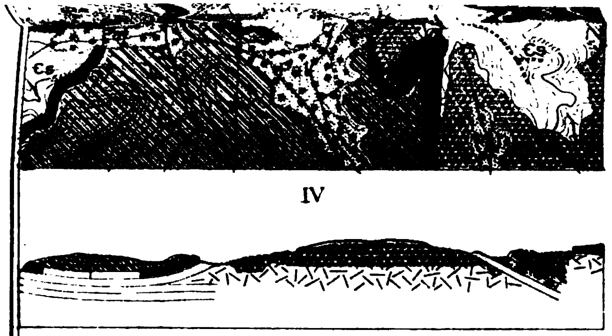
Potter Peak
Pg
Cls
Cml



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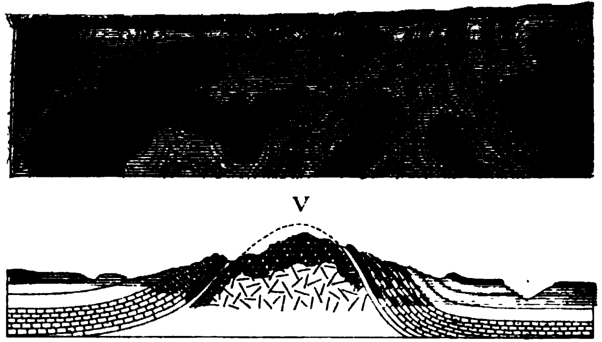

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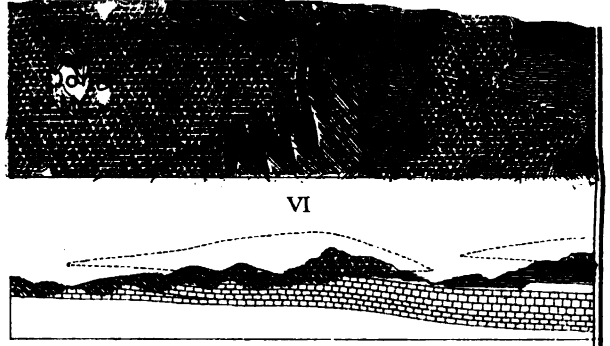

VI

LEGEND

PLEISTOCENE	Pal	Meadow bottom land Alluvium
PLEISTOCENE	Pg	Ancient stream gravels
CRETACEOUS	■	Benton dark shales
CRETACEOUS	▨	Dakota brown sandstone
CRETACEOUS	Kl	Lower Cretaceous sandstones and shales
JURATRIAS — JURASSIC	■	Sandstones limestones and shales
JURATRIAS — TRIASSIC	■	Thick red marls and gypsum
CARBONIFEROUS — PERMIAN	■	Minnekahta thin limestone over red bed
CARBONIFEROUS	Cm	Minnelusa limestones and sandstones
CARBONIFEROUS	▨	Massive limestone
SILURIAN	■	Arenaceous limestone
CAMBRIAN	Єs	Shales, limestones, and sandstone
IGNEOUS	▨	Porphyry
IGNEOUS	╱╳	Dikes

GEOLOGICAL MAPS AND CROSS-SECTIONS

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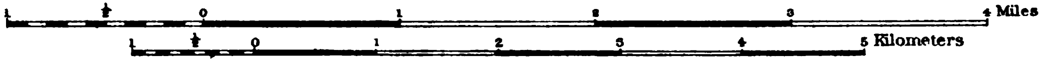

Contour interval 50 feet
Datum is mean sea level

Topography by W. H. Herron and Arthur Stiles

Colored portions of sections indicate rocks exposed

JULIUS BIEN & CO. LITH. N.Y.

somewhat more irregular than in the case of Elkhorn, Sandy Creek occupying a synclinal valley between Crook Mountain and a laccolith to the southwest, and Crook Valley on the east is the northern appressed extension of the Boulder Park syncline.

The drainage features repeat the small concentric rills, the radial smaller streams, and the encircling larger streams. The largest stream of all, however, again as in the case of Elkhorn, does not remain outside of the Permian limestone rampart on the soft red marl, but has cut its channel into the side of the dome, carving out a deep canyon in a lower formation. Whitewood Creek is one of the master streams of the region, having in general, like Polo Creek, a course consequent upon the greater northeast slope of the Black Hills uplift, but it shows at several points evidence of stream capture and diversion due to complications occasioned by irregular distribution of hard and soft beds. In both this case and that of Elkhorn there is a strong suggestion that these greater streams were superimposed upon the laccolith from a position unaffected by the doming when their channels lay stratigraphically higher. Both of them are deflected from a course that higher upstream approaches the dome directly. In the case of Crook Mountain, if this course were continued through the mountain it would cross the summit; in the case of Elkhorn it would cut off a considerable portion of the northwest flank.

In Spiegels Gap, on the northwest side of the mountain, a reversal of drainage through one of the Minnekahta limestone gateways has produced one of the most remarkable topographic curiosities in the Black Hills. The Red Valley makes an abrupt bend northwest of Crook Mountain, and the Red Beds are compressed into very narrow limits on the flanks of the arch. The Permian limestone here forms the crest of an escarpment that rises 400 feet above the bottom of Whitewood Canyon. The small stream occupying the narrowed Red Valley outside of the escarpment joins Whitewood Creek at Crook City. The usual V-shaped gateways through the limestone give evidence of a former radial drainage from Crook Mountain into the Red Valley, but Whitewood Creek, after cutting its deep gorge in the flanks of the dome, has reversed all these streams, and Spiegels Gap, the most conspicuous of the V-trenches, appears like an artificial notch or gash; the overhanging scarp within extends to the bottom of the notch, and within the V the slope is very steep inward toward the mountain, extending down to the bottom of the canyon.

CITADEL ROCK.

In the case of Citadel Rock a laccolith crest has been revealed by a single radial stream gaining the mastery on a dome of the Elkhorn type; annular valleys have been eroded out through Minnelusa sandstone, gray limestone, Silurian, and Cambrian to the porphyry intruded in

Cambrian shales. Compared with Circus Flats, Elkhorn Peak, and Crook Mountain, progressively, the actual elevation of the Citadel Rock laccolith is found to be the highest. Relative to a common base-level as members of a single erosion grade, Citadel Rock should be eaten more deeply than Crook Mountain, the latter more deeply than Elkhorn, and Elkhorn than Circus Flats. That such is the case is made clear by comparison of the several sections constructed in natural proportion and with a common base line 3,000 feet above the sea (Pl. XLI).

Citadel Rock stands as an isolated monolith with vertical walls on a spur that projects into the midst of a circular basin, above which rises a ring-shaped escarpment of limestone 200 feet higher than the top of the Rock and from 400 to 600 feet above the gulches cut in porphyry that encircle it. The two encircling gulches are superposed upon the porphyry from former concentric subsequent stream The dip of the porphyry-Cambrian contact on the crest of the dome was insufficient to carry the drainage down the porphyry slope by monoclinal shifting. The result is an inherited annular drainage on the porphyry.

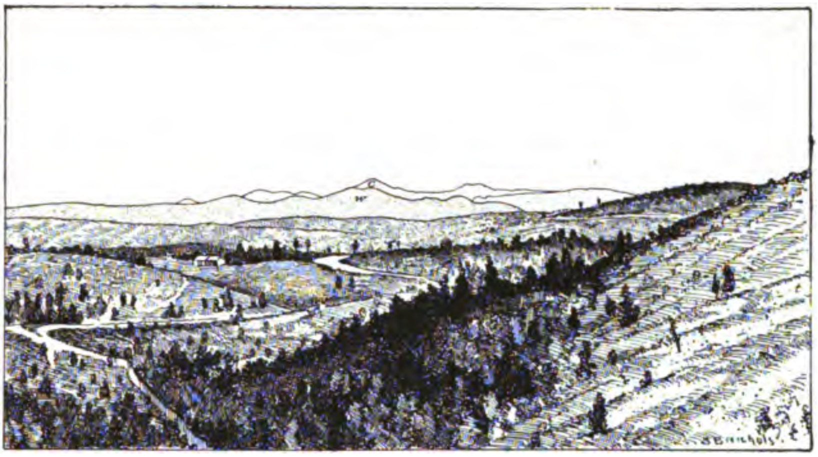

FIG. 97.—Custer Peak and Woodville Hills from Bald Mountain.

The annular drainage of Citadel Rock is not confined to the small streams within the core. A portion of Higgins Gulch partly encircles the laccolith on the west side, and other small streams curve around it in Carboniferous horizons on other sides. Such streams may shift down the dip along soft beds either by capture or by monoclinal shifting until the dip becomes insufficient to produce such shifting. The final result will be a series of encircling streams about or upon a laccolith remnant, and these mark the original outer limits of domical flexure in upper beds, or may define the position of the original rim of the laccolith itself.

Superposed annular valleys.—In Inyankara a more advanced stage of erosion is shown of the same type as Citadel Rock, with an annular valley in porphyry, an encircling escarpment of sediments, and a central peak which rises above the surrounding escarpment. Custer Peak and the Woodville Hills (fig. 97) represent similar phenomena in flatter laccoliths more completely eroded. In these cases the inherited annular valley has lost definition, so that there is left a central peak with peripheral porphyry knobs, a section through basement strata, and only slight remnants of flanking beds. In Little Missouri Buttes a still later stage is shown. No trace of flanking sediments there remains; erosion has eaten through the middle of the laccolith almost to the basement stratum, and the central peak is surrounded by masses of talus on the west and north and by lower knobs on the east and south. There is, however, a distinct remnant of the inherited annular valley about the highest peak of Little Missouri Buttes (Pl. XXXVIII). In the case of Mato Teepee, about which two small gulches and the western bench form remarkably perfect semicircles, the annular valley is inherited on strata underlying the laccolith. This perhaps marks approximately the former border of the porphyry area.

KIRK HILL.

Kirk Hill (Pl. XLI) forms an eastern extension of the Vanocker laccolith. Here erosion has progressed sufficiently to expose porphyry in the region of maximum corrasion on the flanks of the dome, which is still capped, however, by a veneer of Cambrian beds with fingering extensions on the interstream spurs. To the northeast the porphyry is continued into high hills at the head of Deadman Creek. Kirk Hill is thus a laccolithic arm or lobe from a greater mass. The structure of the sediments west and south is synclinal, and on the southeast there is a synclinal sag that separates this lobe from another extension of the Vanocker laccolith.

On Kirk Hill radial small streams are well shown, but since the sedimentary shells which cover the dome have been in great part removed, the small rill beds of concentric subsequent arrangement are lacking, except in a few cases on the southwest side, where Silurian and Carboniferous limestones still form crescentic escarpments over the soft shales. Park Creek is an encircling stream following the western syncline, and other streams encompass the hill on the south, southeast, and northeast. At the northwestern base of the hill Park Creek has cut through the syncline, and for a short distance follows the contact of porphyry with overlying sediments, but at no point has the porphyry mass been dissected to a sufficient depth to reveal the stratum on which it rests.

In topography Kirk Hill marks a stage of denudation later than Citadel Rock, for the flanking sedimentaries have weathered well down the slope of the laccolith, leaving a hill shaped like a low dome with remnants of strata clinging to the summit. The transition from annular valley to rounded hill is a repetition of the process shown between Circus Flats and Elkhorn Peak. Kirk Hill represents the third and last cycle in the development of hills over the laccolith. The first was the hill of Dakota sandstone that preceded the Circus Flats stage; the second was the Minnelusa sandstone hill, represented in the Elkhorn, Spottedtail, and Green Mountain domes; the last case, like Kirk Hill, is represented in Deer Mountain, Dome Mountain, and other laccoliths.

CROW PEAK.

At Crow Peak (Pl. XLI, fig. 5) the porphyry stands at greater height above base-level than at any point hitherto described in this chapter. As a result, erosion has carried down the flanking sediments and left the steep-sided laccolith in high relief. The resistant limestones, however, still cling to the slopes on all sides. Immediately about the mountain radial gullies are conspicuous. Crow Peak on the west and portions of Higgins Gulch on the east and south partially encircle the laccolith. Citadel Rock occurs a mile and a half SSE. from Crow Peak, in the direction of the greater Terry center of irruption. The difference from the Kirk Hill stage consists in the absence of capping Cambrian beds and the greater relief; Crow Peak is also structurally different in its more intense dome flexure.

PILLAR PEAK AND BEAR DEN MOUNTAIN.

The sixth stage of erosion is shown in Pillar Peak and Bear Den Mountain (Pl. XLI), where the beds capping and flanking the laccoliths have been entirely eroded away, and erosion has revealed the underlying strata and some of the conduits through which the intrusive rose (see Pl. XX for general relations). On the south is shown the stratigraphic series, from Algonkian through Cambrian, Silurian, Carboniferous, Minnelusa, and Permian, which underlie the Bear Den laccolith at its northern end. Bear Den Gulch separates the Bear Den laccolith from the Dome Mountain mass, on whose eastern flanks the limestones dip steeply under the Bear Den laccolith, and thence the dip diminishes to a condition of approximate horizontality in a broad, flat depression northeast. In Cambrian beds about the town of Galena are shown sills and a dike complex that marks the locus of intrusion for the Bear Den porphyry, which spread northeast, breaking across strata. The initial structure of these laccoliths was a great, swollen mass beneath Silurian and superincumbent strata on the present site of Dome Mountain, and smaller offshoots which broke across and domed up higher beds. The lower side of a strike fracture across limestones may be followed from Dome Mountain to Pillar Peak. It is probable that this fracture extended across Lost Gulch, and that Pillar Peak and Bear Den Mountain were at one time continuous, the lower contact of the porphyry progressively truncating strata along a horizontal fracture plane across gentle northeast dips. The west side of Pillar Peak shows porphyry on gray limestone. On the east side of the same mountain the porphyry overlies Minnelusa sandstone. The Bear Den porphyry overlies Permian limestone in the northern part of the mountain.

Considering Pillar Peak and Bear Den Mountain parts of a single laccolith, the drainage is seen to have produced an inner basin, a horseshoe ridge, and outer encircling drainage. The inner basin is Lost Gulch, cut through the basement strata; the horseshoe ridge is of porphyry, composed chiefly of the laccolith remnants; Two Bit and Bear Butte creeks, encircling the whole, probably define the original laccolith perimeter, though now their canyons are cut in limestone below and away from the porphyry. As a stage beyond that of Kirk Hill in physiographic development, this horseshoe ridge of porphyry is like the limestone ridge about Citadel Rock. Lost Creek, the north-flowing stream on the former hard rock hill, worked faster than the other radial streams and gnawed through the porphyry to softer rocks below, there to erode out an interior basin. This is the third and last stage of inner basins. The first was Circus Flats, with a Dakota rim; the second, Citadel Rock, with a Carboniferous rim; and in the Pillar-Bear Den case the rim is formed of porphyry. Stratigraphically the last case differs from the others, for the horizon of intrusion is higher. Other types of the last stage are numerous; a horseshoe-shaped laccolith remnant incloses the city of Lead; Ragged Top is shaped like a crescent and is encircled by two pairs of streams. Woodville Hills, Custer Peak, and Little Missouri Buttes retain a central high peak with an annular valley in porphyry about it, and the outer crescent of porphyry has a number of culminating summits.

SUMMARY OF EROSION STAGES.

The cases cited show that laccolithic domes deflect regional master streams, and that subordinate drainage conforms strikingly to the relative resistance of rocks exposed. An early stage produces a dome-shaped hill with radial drainage. One radial stream gains advantage over its fellows and eats out the central portion of the dome to a soft stratum beneath. The outward dipping hard beds are undermined and drainage formerly radial outward becomes radial inward; a former mountain becomes a quaquaversal basin inclosed by a horseshoe ridge. Recession of this ridge and continued erosion on the soft bed uncovers an arch of harder rock. Monoclinal shifting on the soft bed becomes easier than deep cutting into the dome, so that the flanking beds are eroded down and a new radial drainage forms with two pronounced encircling streams (fig. 98). In the figure the radial progression from the Circus Flats stage through the several stages described is shown by profiles inscribed on a common dome. The alternations from domical mountain to horseshoe-shaped ridge will continue under the erosive action of changing subordinate drainage until the porphyry is reached. Here monoclinal shifting is no longer possible, owing to lack of monoclinal structure. Annular drainage superposed on the crest of the laccolith may persist so as to be retained as a characteristic feature of both plan and profile in old laccolithic mountains. If the last monoclinal shifting takes place along the contact of porphyry and capping sediment, annular drainage which has shifted down this contact will eventually be superposed upon the stratum beneath the laccolith, marking there a peripheral limit for the original igneous mass even after the porphyry has been eroded away.

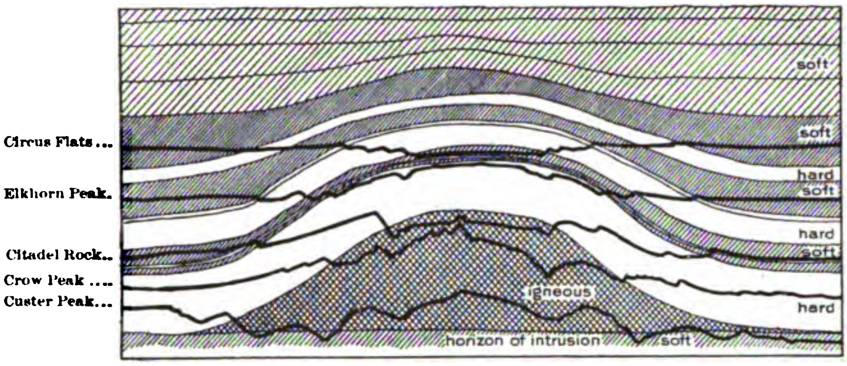

FIG. 98.—Diagram illustrating development of erosion profiles on laccolith domes.

EROSION PROFILES.

The section diagrammatically represented in fig. 98 corresponds in thickness and consistency to the Paleozoic section from Silurian limestone to Pierre shale and higher. A laccolith is represented in the normal position, under the "competent" Siluro-Carboniferous member. The three hard members, progressively thinner upward, are Siluro-Carboniferous, Jura-Cretaceous, and Niobrara; the three soft members, progressively thicker upward, are Red Beds, Benton, and Pierre. These thicken at the sides of the arched hard strata, and the dome consequently fades out to horizontality above. The profiles show types, represented by separate cases in the Black Hills, made by laccoliths intruded at about the same horizon. These profiles are projected irrespective of scale, on the cross section of an ideal dome, to show their mutual relations to a uniform process of erosion.

In Circus Flats there is a basin on a soft stratum; in Elkhorn the basin is divided in two by the resistance of the central hard stratum, and the two lateral depressions mark the encircling drainage. In Citadel Rock the dome has been eaten through and the basin is repeated, with higher walls, because encompassed by the thicker and harder limestone; annular drainage is superposed on the porphyry. In Crow Peak the porphyry shows greater power of resistance to erosion, and streams are gnawing along the contact of laccolith and sediments. In Custer Peak several pairs of annular streams have been superposed on the porphyry; some of these have cut through to the basement strata, and only on one side is the laccolith rim preserved. The conspicuous feature of the profile is the bilateral symmetry of central peak and lateral spurs. The outermost streams that can be traced as encircling the mountain lie within the original limits of the porphyry.

LITTLE MISSOURI BUTTES AND MATO TEEPEE.

Little Missouri Buttes and Mato Teepee mark two stages further, but their profiles can not consistently be inserted on this diagram, because their basement strata are Jura-Cretaceous; otherwise the process is the same. If we denude the Custer Peak profile a little further, removing all trace of flanking sediments, and leave a steep central peak, a lower knob on one side, and a train of talus on the other, we shall have the profile of Little Missouri Buttes (see Pl. XXXVIII, section). If we leave only a small columnar remnant of porphyry with an annular valley in the sediments about it, we shall have Mato Teepee (fig. 95). In this erosion scheme the conduits have no considerable effect; they are dikes or lateral sills, which may be eroded soon or late in the process, according to their position.

RELATION OF PRESENT ELEVATION TO DEPTH OF EROSION.

Laccoliths intruded about the same horizon are more deeply denuded in proportion to their present height above base-level; the following table shows the relative heights above sea level of the profiles (compare fig. 98), from deeply buried laccolith in the plains to porphyry remnant in the Hills:

	Present profile.	Crest of laccolith (approximate).
	Feet.	*Feet.*
Circus Flats	3,000	2,500
Elkhorn Peak	4,520	4,000
Citadel Rock	5,450	5,500
Crow Peak	5,785	6,000
Custer Peak	6,812	7,500

This table gives present altitudes of topography immediately above or below the initial crest of the laccolith. In Citadel Rock the altitude is nearly that of the actual porphyry upper contact; in Circus Flats and Elkhorn Peak the porphyry probably lies from 500 to 800 feet below; in Crow Peak and Custer Peak much has been eroded away. Therefore the actual differences in elevation of the laccoliths were greater in every case, as shown in the second column of the table. As all of these were intruded under and arched Siluro-Carboniferous limestones, and the depth of their uncovering (fig. 98) varies with their height above sea level, it is clear that the present profiles are products of an erosion process which affected all alike. Hence the grouping of individual cases in series to represent erosion stages is justified by their relation to a common base-level.

CHAPTER IV.

THEORETICAL CONCLUSIONS.

SUMMARY OF FIELD EVIDENCE.

In the preceding pages it has been shown that igneous intrusions of rhyolite and phonolite porphyries accompanied or immediately followed a great movement or uplift in the area now occupied by the Black Hills. This uplift arched the horizontal strata of the plains into an elongate dome; schists beneath, with nearly vertical bedding and lamination, moved up by faulting and slipping, frequently on planes of schistosity. Erosion has removed a portion of the sedimentary cover completely, exposing two kinds of sections whereby the solid geometry of structures within the uplift may be studied. One is a beveling across the top of the dome, exposing a ground plan; the other is a deep trenching by streams through the flanks, exposing vertical cross sections. The igneous matter rose through the steeply inclined schist laminæ and spread out among the sediments which lay across them unconformably. Erosion beveling has exposed dikes in the schist and flat masses in the later strata. The walls of erosion trenches show the thickness of the sills and lenses and sometimes their junction with feeding dikes.

The intrusives are confined to the northern portion of the uplift. The southern portion was occupied by massive ancient pegmatite granites, themselves pre-Cambrian intrusives in Algonkian strata. Probably they acted as a rigid cementing and hardening agent to prevent fracturing in the southern schists; the northern, less indurated phyllites cracked and faulted more readily to permit the younger intrusives to rise from the depths. The northern exposed schist areas contain many hundred dikes and some stocks; these must have induced movements of horizontal extension in the schist, and such movements are attested by bedding plane faults at the base of the Cambrian. The dikes have a common trend and dip parallel with schistosity. The dip gave them tendency to spread in the Cambrian in one direction more readily than in another. In Cambrian thin-bedded strata with many shale horizons, sills formed in great number. Above lay the thick limestone; it resisted upward movement of the porphyries and locally became domed and arched. Beneath it were found the principal laccoliths of larger size, the largest where the limestone was thinnest. Some of them were unsymmetrical, partly because they were injected into strata possessing an initial dip, partly because their conduits sloped and the magma was forced forward in one direction. On one side the limestone was flexed beyond the breaking point; a fracture opened and admitted the igneous fluid to higher horizons, forming subordinate laccoliths. The subordinate laccoliths are characterized by still greater lack of symmetry; their sides are steeper than those of the main laccolith; they fault and crumple the beds about them. Associated with dikes, sills, and laccoliths are breccias composed of fragments of the rocks through which the igneous magma passed. There is no evidence that the intrusives were connected with surface volcanics. In general the phonolites are younger than the rhyolites; none of the larger main laccoliths are formed wholly of phonolite; the phonolite broke through the larger bodies of rhyolite-porphyry and solidified in smaller masses at higher horizons. The greater number of subordinate laccoliths, however, are of rhyolite-porphyry; these include Bear Butte, Deadman, and Whitewood Canyon laccoliths, Crow Peak, Inyankara, and Sundance Mountain. The magmas which formed the subordinate laccoliths were beginning to solidify and hence were more viscous; this is proved in part by fewer sills, by domes of smaller ground plan and greater convexity, and by diminution in total volume of intrusive rocks in the higher strata. The characteristic forward and upward movement of intrusive through strata is by way of strike fissures. The lower contact of sills and laccoliths frequently truncates or bevels strata obliquely across the bedding. The horizons where a single stratum is followed for some distance are composed of soft shale confined between harder beds.

Erosion has left laccoliths covered, partially uncovered, and deeply dissected, and in places has removed them entirely or left only scattered remnants. Conduit, basement contact, wedge, flank, crest—all parts of the laccolith are exposed, in plan and section, in different places in the Black Hills. The evidence quoted points to Eocene time as the age of intrusion. There were several thousand feet of strata above the laccoliths, and the soft Cretaceous shales absorbed laterally the doming produced by individual intrusive masses. Trunk drainage consequent on the Black Hills uplift was deflected by adjustment to the domed hard strata that were gradually uncovered; branch drainage, dependent on the relation of rainfall to form and texture of surface, continually changed with the discovery of hard and soft strata, producing hills in hard domed beds and annular valleys in soft ones. Such annular valleys were eventually superposed on porphyry, and persist in several deeply dissected laccoliths, such as Custer Peak and the Woodville Hills. Where an annular valley on the contact of porphyry and flanking sediments became superposed on the basement stratum, its course preserved approximately the outline of the laccolith after the same was in great part eroded away.

HISTORY OF INTRUSION.

The history of intrusion in the northern Black Hills is believed to be intimately associated with the history of the larger deformation. Intrusion is not conceived to have been in any sense a cause of the greater uplift, but an effect. The intrusions were a small incident in a great movement of elevation. The greater uplift probably took place after the close of the Laramie, along with similar movements in the Bighorn Range and the Rocky Mountains. Whatever their cause, these movements were colossal and involved a considerable section of the earth's crust; doubtless there had been similar movements about the hard granite core of the Black Hills from the earliest Paleozoic times. There was unquestionably some deformation prior to the laccolithic intrusions, for these broke across previously brecciated Cambrian flags, and encountered dips already initiated. The post-Laramie uplift was accompanied by profound fracturing. The fractures reached downward to a zone where molten rock was under pressure. The liquid shot upward into every ramification of the fracture system; Algonkian, Paleozoic, and Mesozoic beds were in some sense under compressive stress, rising slowly, the hard, competent members supporting the arch, the soft beds following the lead of their more resistant neighbors. Diversity of structure and consistency produced minor differential movements of faulting and folding. The upturned schist beds slipped like cards on edge to make undulations in the basal Cambrian quartzite, which also faulted in places. Springing into every weak place, spreading the beds and crumpling the soft ones wherever there was tendency to gaping by reason of the greater burden assumed by the more rigid strata, the igneous magmas reached the Cambrian through countless fissures in the schist beneath. The change in structure at the Algonkian-Cambrian unconformity was especially favorable to the development of local weakness that would give advantage to an igneous wedge. The Paleozoic horizon least compressed lay under the Carboniferous limestone. The thick limestone member, most "competent" to support load under lateral pressure, relieved the soft shales beneath in many places. The porphyry magma was itself probably under pressure and capable of independent dynamic action relative to individual beds invaded; whether that pressure was in any way limited by the actual volume of magma available, or what hydrostatic or thermal law governed it, we have no means of knowing, but it is quite certain that the pressure of igneous fluid relative to the condition of the limestone was sufficient locally to arch up and break through that stratum and some of the superjacent beds. That it did not do this until it was beginning to solidify is in part suggested by the fact that only a relatively small volume of porphyry broke through the limestone to higher horizons. The fact of local doming and fracturing of the limestone by the porphyry does not of necessity imply that the lava in each of those domes lifted the load; it bent and pimpled the limestone within an arch of enormously greater magnitude, composed of several competent members that were collectively supporting the total weight of sediments. The fact that the greatest doming of limestone over porphyry at the Terry-Polo complex took place where the limestone was thinnest shows that it was not the weight of superincumbent beds, but the inflexible quality of the thicker limestone which resisted doming. It is equally clear that the size of the laccolith is entirely independent of load; the smaller Ragged Top and the greater Deer Mountain laccoliths are both intruded at the same horizon; the Vanocker porphyry mass, probably the largest single laccolith exposed, reaches the Upper Carboniferous, while comparatively small subordinate laccoliths, like Crow Peak and the one in Whitewood Canyon, are intruded under Obolus beds at the base of the Cambrian.

APPLICATION OF EXPERIMENTS.

Mr. Howe's experiments prove that low viscosity favors wide lateral extension to form sills; high viscosity produces thick lenticular bodies. They show, also, that the intrusive thickens into domes where a resistant overlying stratum locally thins. Howe has demonstrated further that a stratigraphic obstacle to horizontal spreading may cause a sill to thicken into a laccolith. This was the first effect of the initial dip encountered by the Dome Mountain magma in spreading, and of the upward bend over the earlier Warren Peak uplift encountered by the Little Missouri Buttes magma when injected through horizontal beds. The first experiment shows that irregular serpentlike bodies may push their way through thick beds of incoherent material; this is analogous to the irregular intrusions at Portland. In a dome of hard beds radial fractures form on the crest and concentric fractures open downward on the periphery. The former, if developed by erosion, would guide radial drainage; the first peripheral fractures give egress to the intrusive to form subordinate laccoliths. Such overturned domes as Ragged Top or Bear Butte, thickest on the sides away from the conduit, are well illustrated in Experiment IV, where it is shown that a magma rising through an inclined conduit forms an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical.

DISCUSSION OF PUBLISHED THEORIES AND DESCRIPTIONS.

EFFECT OF LOAD (GILBERT).

The Black Hills, like the Henry Mountains, contain smaller laccoliths in the upper zone and larger ones in the lower. This is believed by the writer to be due solely to increased viscosity, diminished pressure of injection, and more incoherent beds in the upper horizons. Gilbert gave less value to the influence of viscosity and greater value to variation in load. He concluded "the pressure of injection remaining constant, the limital area of a laccolite is a direct function of its depth beneath the surface. The limital area is greater when the depth is greater, and less when the depth is less."[1] This conclusion was reaffirmed by Gilbert in the fall of 1896 in connection with his description[2] of Twin Butte. So far as our experiments go, they seem to indicate that the dome curvature of a laccolith is greater under a greater load, hence for the same volume of intrusive the area is smaller. In an experiment with a load of shot on the surface of strata, they were domed up rapidly in the center; without the shot the laccoliths spread out more widely and formed a lower arch (Experiments IV and V). In both cases the injected wax was cooled for the same period and was uniformly viscous. Under greater load the shale horizons are more closely compacted and less easily split apart. With the same viscosity and pressure of injection an intrusive lens under load can more easily increase its convexity to produce lateral thickening and crumpling of superjacent soft beds than it can spread as a wedge to lift a great volume of heavy strata. Hence, in those cases where load has any effect, if viscosity, volume of magma, and pressure of injection are constant, the area of a laccolith is probably greater when the depth is less. This appears to reverse Mr. Gilbert's conclusion, but the constants mentioned alter his problem, and the experimental analogy is incomplete. The influence of varied load is believed to be inconsiderable in the Black Hills, so much greater was the influence of varied viscosity and pressure of magmas and texture of beds invaded. The size and curvature of individual laccoliths were modified by variation in thickness of the stratum immediately superjacent, by texture and thickness of the shale horizon selected for intrusion, by distance from and dynamic relation to conduits and other laccoliths or sills, by stratigraphic obstacles, and by concomitant regional folding and faulting. The composition of magmas may have had some effect, too, in determining rate of solidification and consequent viscosity.

ANALOGOUS DESCRIPTIONS BY HOLMES.

The absorption of doming vertically was suggested in a paper by Holmes published in 1877, where, in describing the Sierra El Late, a typical laccolith was figured[3] diagrammatically, though such structures were as yet unnamed. The figures compared show "arching of strata produced by intrusion of single mass uniformly distributed" (a laccolith) and "degree of arching really produced by the irregular intrusions." The second figure showed much less arching, due to "a sort of absorption of the shales, so that at least half of the space through which the trachyte is distributed is occupied by the crushed and metamorphosed fragments of shale." Most observers agree that shale beds are favorite horizons of intrusion.

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[1] Geology of the Henry Mountains, p. 84.

[2] Laccoliths in southeastern Colorado: Jour. Geol., Vol. IV, 1896, p. 821.

[3] Hayden's Report, 1875, U. S. Geol. and Geog. Surv. Col. and adjacent Terr., p. 272, Pl. XLVI, fig. 2.

The intrusions of basalt in Mount Everts, in the Yellowstone Park, figured by Holmes[1] (fig. 99), show a relation of conduit to intruded lens or sill, similar on a small scale to that of the subordinate laccoliths of the Black Hills (compare sections Pl. XXI). These basalt masses are said to be intruded in Cretaceous sandstones, shales, and lignite, the beds dipping 5° to 13.°

> [The intrusions] cross from horizon to horizon, breaking through the beds and pushing them aside, and bending and crushing them in a most remarkable manner. * * * The masses * * * are very irregular in thickness, reaching in places 40 to 50 feet. They lie in rude sheets approximately with the strata, but bearing the strongest evidence of their intrusive character. The irregular bed that outcrops along the crest of the ridge is in places 40 feet in thickness, but generally falls far short of this. Its position in the strata points very clearly to its intrusive character. It does not lie in any one horizon, but breaks across the strata at all angles, crushing the severed edges back upon themselves. * * * It rests chiefly in a series of coal shales and sandstones. * * * In the heavier masses this basalt has a rudely columnar structure and weathers down in very small angular blocks. In the thin tongues that have been thrust out from the main mass into the surrounding strata, there is a tendency to form small prisms at right angles to the surface. * * * The strata which inclose this basalt dip to the northeast at angles from 10° to 15,° the line of the great fault which defines their northern limit being about 2 miles distant. It seems probable that the intruded basalts may have originated in or rather reached their present position through this fault, the crushing of the strata indicating generally an intrusion from that direction.[2]

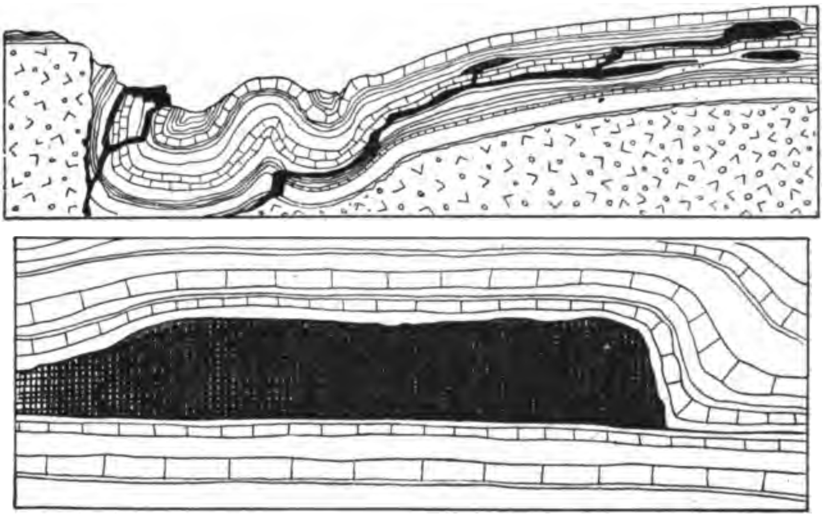

FIG. 99.—Intruded basalts of Mount Everts, Yellowstone Park (Holmes)

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[1] Hayden's Report, 1878, II, U. S. Geol. and Geog. Surv. Terr., p. 10, Pl. VI.

[2] Op. cit., pp. 10, 11.

The lower enlarged figure is a mass seen in the western face of Mount Everts, and in form is remarkably like the end of an unsymmetrical laccolith with lateral conduit (Experiment IV, Pl. XLIV). It is a mass "300 feet long by 12 to 15 feet thick, and appears in the face of a steep wall of dark shales and laminated sandstones. It has been forced in between the yielding strata, folding them up almost at right angles at the ends, as shown in the figure" (fig. 99).

WORK OF CROSS, WEED, AND PIRSSON.

The bibliography of laccoliths was thoroughly reviewed by Cross,[1] and other descriptions of laccolithic mountain groups in Montana have recently been published by Weed and Pirsson.[3] Cross recognized in the Mosquito Range and Tenmile district the influence of orographic movements concomitant with intrusion. He says: "In regions where the beds are under orographic stress, almost or quite to the point of folding, a magma would find intrusion on certain planes a comparatively easy matter." Cross points out the prevalence of departures from regularity due to oblique intrusion across bedding, structural weakness, earlier intrusives, and incoherent strata. His sections through Mount Marcellina and the Anthracite Range, unsymmetrical laccoliths, are closely similar to cases in the Black Hills. In his ideal restorations of arched strata above Mount Marcellina the size of the arch in strata far above is represented as greater (in dip length) than that of the stratum next to the laccolith, a questionable construction if any of the strata involved are soft and yielding.

Pirsson's sections from the Judith Mountains express the relation of main laccoliths to subordinate peripheral bodies. He concludes that the important factors in the production of laccoliths are pressure of injection, viscosity, gravity, load, and cohesion of strata. His discussion of cause, comparing the mechanism to a "vast hydrostatic press," seems to neglect the possibility of orogenic deformation preceding and initiating intrusion. "Suppose a fissure extending upward through comparatively undisturbed strata and forming a dike, and that it does not reach the surface." This is Professor Pirsson's premise. Such a fissure could only arise from differential shortening of strata in an arc of the earth's crust. Pirsson conceives that the force of injection is partly expended in overcoming internal viscosity and gravity, and "whatever remains over above these two is used in lifting the sediments." No mention is made of lateral expenditure of energy in folding and faulting strata, except that "resistance to splitting" is believed to influence resulting laccolithic structures.

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[1] The laccolithic mountain groups of Colorado, Utah, and Arizona, by Whitman Cross: Fourteenth Ann. Rept. U. S. Geol. Survey, Part II, 1893, p. 157.

[2] Op. cit., p. 236.

[3] Geology and mineral resources of the Judith Mountains of Montana, by W. H. Weed and L. V. Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, p. 437 Geology of the Little Belt Mountains, Montana, by W. H. Weed, accompanied by a report on the petrography of the igneous rocks of the district, by L. V. Pirsson: Twentieth Ann. Rept. U. S. Geol. Survey, Part III, 1900, p. 387.

It seems to the writer that the hydrostatic press analogy must not be pushed too far; it necessitates preexistent or gaping conduits through which lavas rise to spread out "at some horizon where the conditions are right,"[1] The lava is required to do all the work of lifting superincumbent strata by breaking and splitting its way forward. If the dynamic conditions of the Rocky Mountain region gave evidence of quietly gaping internal fissures with strata otherwise undisturbed, it is quite probable that, when the fissures were full of lava, under some obstacle to further upward flow, the lava would penetrate soft beds horizontally and lift the load, were the pressure of injection sufficient. But the orographic stress which raised thousands of square miles by great folds and faults all through the Rocky Mountains produced results on an enormously greater scale than what is observed in small laccolithic mountain groups. In many places intrusions accompanied or followed the greater movements; in many places faults and folds occur contiguous to laccoliths. The greater the horizontal extent of a warp of gentle curvature the less conspicuous it will be in a region where intrusives are very conspicuous; yet the fold will lift the load and generate fissures and weak places where the intrusive may expend its energy in localized splitting and arching of strata. The Henry Mountains and the Judith Mountains are laccolithic mountain groups where no connection is observable between regional deformation and laccolithic intrusion; yet great folds and faults are shown to exist in the immediate vicinity of the Henry Mountains.[2] In the Black Hills the relation between orogenic deformation and intrusion can be clearly traced only in the region of conduits (p. 188); in the other mountain groups no deep conduits have been described.

"PLUTONIC PLUGS" AND "SUBTUBERANT MOUNTAINS."

This discussion would be incomplete without some reference to Professor Russell's theory of "plutonic plugs" and "subtuberant mountains."[3] After a visit to the Sundance Hills and Mato Teepee, Russell concluded that these intrusions differed from laccoliths in being less spread out horizontally, and he called them "plugs." Bear Butte and Inyankara are still better examples of pluglike forms; they are steep-sided laccoliths of small size. The word "plug" seems to the writer an unnecessary one, and somewhat misleading, as it suggests the stopper for a circular hole. Owing to his failure to visit the dike district, as Mr. S. F. Emmons[4] has shown, Russell was unfamiliar with the lateral conduits characteristic of subordinate laccoliths, and his casual visit to Mato Teepee led to the unwarranted conclusion that the conduit lay beneath.

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[1] Pirsson, Judith Mountains, p. 584.

[2] Gilbert, Geology of the Henry Mountains, p. 11.

[3] Jour. Geol., Vol. IV, 1896, pp. 23, 177.

[4] Science, N. S., Vol. X, No. 236, 1899, p. 24.

The comparison of small domes with great ones led to the suggestion that possibly such uplifts as the Black Hills, Bighorns, or Park Range were occasioned by the injection of igneous cores. For some reason stress is laid on the fact that the present cores of the uplifts are granite, though it is also stated that these granites are usually ancient ones from which the encircling sediments were derived. The name "subtuberant mountains" was suggested for such uplifts. There is, it is true, an attractive similarity between the drainage of the Black Hills and that of Circus Flats or the Bearlodge Range. Both are quaquaversals with radial streams. Beyond this there is no structural similarity. The Harney granite is pre-Cambrian. If an intrusive in the depths occasioned the great uplift in laccolithic fashion, there is no evidence for the existence of any horizontal splitting planes on which it might spread. The Rocky Mountain ranges are not smoothly elliptical, but irregular, elongate, and frequently bent; even the Black Hills mass has extensions northwest and southwest that show it is not a simple dome.

There are Tertiary granites and diorites in the Cordilleran district, and undoubtedly the intrusives as a whole added their share to movements of extension. It has been shown that in the northern Black Hills the schists were extended laterally by dikes that invaded them; the sediments above were displaced both horizontally and vertically by dikes, sills, and laccoliths that increased their bulk by a few cubic miles. Throughout western North America there have also been great uplifts of an Archean complex, accompanied by folding and faulting that affected later rocks. Much of this deformation was contemporaneous with intrusion. What are the criteria to suggest which was cause and which effect?

An answer to this question is suggested by extending Professor Russell's analogy to its logical conclusion. We are convinced that the doming of beds over the laccolith is due to the intrusion of igneous rock. The criteria that lead to this conviction are that many stages are found with igneous rock at the core, that the conduit is shown in definite relation to beds deformed and shape of laccolith, that the process may be imitated in miniature experimentally, that no such domes without an igneous core are found in the region, and that the igneous material is the larger feature more conspicuously in evidence than the deformation that it causes. There are large masses of porphyry, but its intrusive character is proved by small railroad cuts and canyon sections. Compare with this the arching of great mountain ranges. Large igneous cores intruded at the time of uplift are not usually found; the conduit is not shown in relation to beds deformed; experimentation in miniature produces such folds by horizontal pressure;[1] such uplifts are found in many regions without an igneous core; and deformation is the large feature, more conspicuous than the intrusives. Moreover, the latter are frequently found related to deformation as an effect. Volcanoes and intrusions occur along fault lines, or, as in the Black Hills, intrusives locally rise through fault fissures and distort folds, the same faults and folds occurring elsewhere as parts of a movement immeasurably greater than anything accomplished by the igneous rocks.

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[1] The mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, 1892.

"BYSMALITHS."

Iddings[1] has described Mount Holmes, in the Gallatin Range, as a mass of dacite-porphyry 3 miles long and 2 miles wide, which was believed to have forced upward "a more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth or might terminate in a dome of strata resembling the dome over a laccolith." The name "bysmalith" was invented for application to such fault laccoliths. The only fault described is a great one, affecting Archean and Paleozoic strata and extending far to the northward from the west side of the igneous body, and as this was stated to have probably acted as conduit, it was not immediately occasioned by the intrusion. Sections are presented[2] representing a stock-like mass in nearly horizontal strata, and over one of these was drawn a reconstruction of 10,000 feet of domed strata with a cone section faulted, which passes into a fold above. The arch immediately above the igneous rock of Mount Holmes is represented with a dip length of 1¼ miles, while 9,000 feet higher the arch has greater curvature and a dip length of nearly 3 miles. In the descriptive portion of the text, which is brief, it is stated in one place that "nearly two-thirds of the circumference of the Holmes mass is exposed as a nearly vertical plane of contact crossing almost horizontal strata." Another statement is that "in all cases examined the neighboring limestones dip away at angles of 40° to 55°." These statements seem contradictory. In the diagram section the dips shown are from 2° to 10°. The sections and the text indicate that the mass described resembles the steep-sided laccoliths of the Black Hills, and that it breaks across strata, in the manner of a stock.

UNSYMMETRICAL LACCOLITHS.

There seems to the writer to be no need in a classification of igneous bodies for hypothetical forms. Faults occurring in a closed curve, while not impossible, are dynamically improbable. The first fault formed over an unsymmetrical laccolith is at one side and usually prolongs itself. Others may form from displacement on radial or peripheral fractures in the region of maximum flexure. As soon as such fractures open however, they fill with magma that releases the strain and forms new subordinate bodies. Such bodies have been described in detail in this paper in the sections treating of Whitewood Canyon laccolith, Pillar Peak, Deadman and Tilford laccoliths, Bear Butte, and Ragged Top Mountain. Mount Marcellina, described by Cross, Black Butte (Judith Mountains) and Barker Mountain (Little Belt Mountains), described by Weed and Pirsson, and Mount Hillers, described by Gilbert, all show similar sections. Structures of this kind have now been recorded in sufficient number to show that the unsymmetrical laccolith with lateral conduit is a common type. Thunder Mountain, in the Little Belt Mountains, described by Weed and Lindgren,[1] shows sections closely similar to Crow Peak (fig. 93). Weed calls it an irregular laccolith or "bysmalith," but states that the cross section is strikingly like that of Mount Hillers, which is a typical unsymmetrical laccolith.

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[1] Mon. U. S. Geol. Survey, Vol. XXXII, Part II, 1899, p. 16.

[2] Op. cit., Pl. V.

SUMMARY OF THEORETICAL CONCLUSIONS.

The following are the theoretical conclusions of this paper in brief: Laccoliths, as shown by Gilbert, are subterranean volcanic phenomena which do not reach the surface, and in the Black Hills they resemble volcanoes in being accompanied by breccias. As they solidify beneath the surface, they cool and become more viscous upward. The lower laccoliths are large because of obstruction by massive strata; the upper ones are small and steep-sided because the magma is more viscous, is probably under diminished pressure, is diminished in volume, and is intruded in soft, thick shales. The upper laccoliths are usually subordinate unsymmetrical offshoots of the lower. The lower main laccoliths frequently show some bilateral or concentric symmetry to the conduit. The conduits are usually dikes. The load may be lifted by orogenic forces, while the intrusion is a subordinate feature permitted by fracture. Laccolith arching is transmitted radially upward only by competent hard strata, and is absorbed laterally by shales. The bottom of the laccolith is not usually a single stratum, but an oblique plane which truncates strata. The conduits of subordinate laccoliths are fractures, gaping downward in hard strata on the flanks of main laccoliths. The texture of strata is important in determining intrusion horizons; shale beds are favorable horizons for intrusion; alternations of shales and hard strata, thin bedded, favor the production of sills. The inclination of a conduit strongly affects the direction of spreading of a sill or laccolith. By lateral deformation the laccolith doming may be completely absorbed upward in thick shales, so that higher beds lie horizontal. Trunk drainage superposed on the dome is deflected by hard beds; branch drainage becomes continually readjusted by monoclinal shifting and capture. Annular valleys are characteristic, and may be inherited from sediments above, by superposition on igneous rock beneath.

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[1] Tenth Census, Vol. XV, 1886, pp. 696-737.

CHAPTER V.

EXPERIMENTS ILLUSTRATING INTRUSION AND EROSION.

By Ernest Howe.

INTRODUCTION.

Gilbert has shown that in the Henry Mountains a liquid or viscous magma rising from the interior of the earth, instead of reaching the surface and there building volcanic mountains by successive eruptions, has "stopped at a lower horizon, insinuated itself between the strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap."[1] As a result of the intrusion the superjacent strata were domed upward, fractured, and otherwise deformed. To intrusive bodies of this type Gilbert gave the name "laccolites" (laccoliths).

The following experiments were undertaken with a view to imitating as far as possible the processes involved in the formation of laccoliths and the resulting deformation of the invaded beds. In general, the method employed was to supply certain theoretical conditions and to attempt to construct the laccolith under these conditions.

ACTIVE AND PASSIVE AGENTS.

The agents which govern the development of a laccolith are of two kinds and may be termed, for convenience, active agents and passive agents. The active agents are the viscous or liquid magma and the force which causes this magma to rise from the heated interior of the earth and intrude itself between certain layers of the sedimentary rocks of the earth's crust. These sedimentary rocks and the physical properties peculiar to them are the passive agents. In taking up these experiments the problems were to supply, first, a series of stratified deposits which would correspond to those found in nature, and, second, some liquid or viscous substance which might be injected into the sediments and which would subsequently solidify. The first presented no serious difficulties. It was found that an excellent sedimentary column could be made by sifting plaster of paris, coal dust, marble dust, and sand into a shallow tank containing water. The plaster solidified after settling and its relative rigidity might be considered as corresponding to that of massive limestone in nature. The coal dust served as a substitute for shale, and the marble dust and sand took the place of sandstones. A number of materials suggested themselves as suitable for the intrusive magma, but the means of injecting them presented mechanical difficulties.

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[1] Geology of the Henry Mountains, by G. K. Gilbert: U. S. Geog. and Geol. Survey Rocky Mountain Region, 1877.

PRELIMINARY EXPERIMENTS.

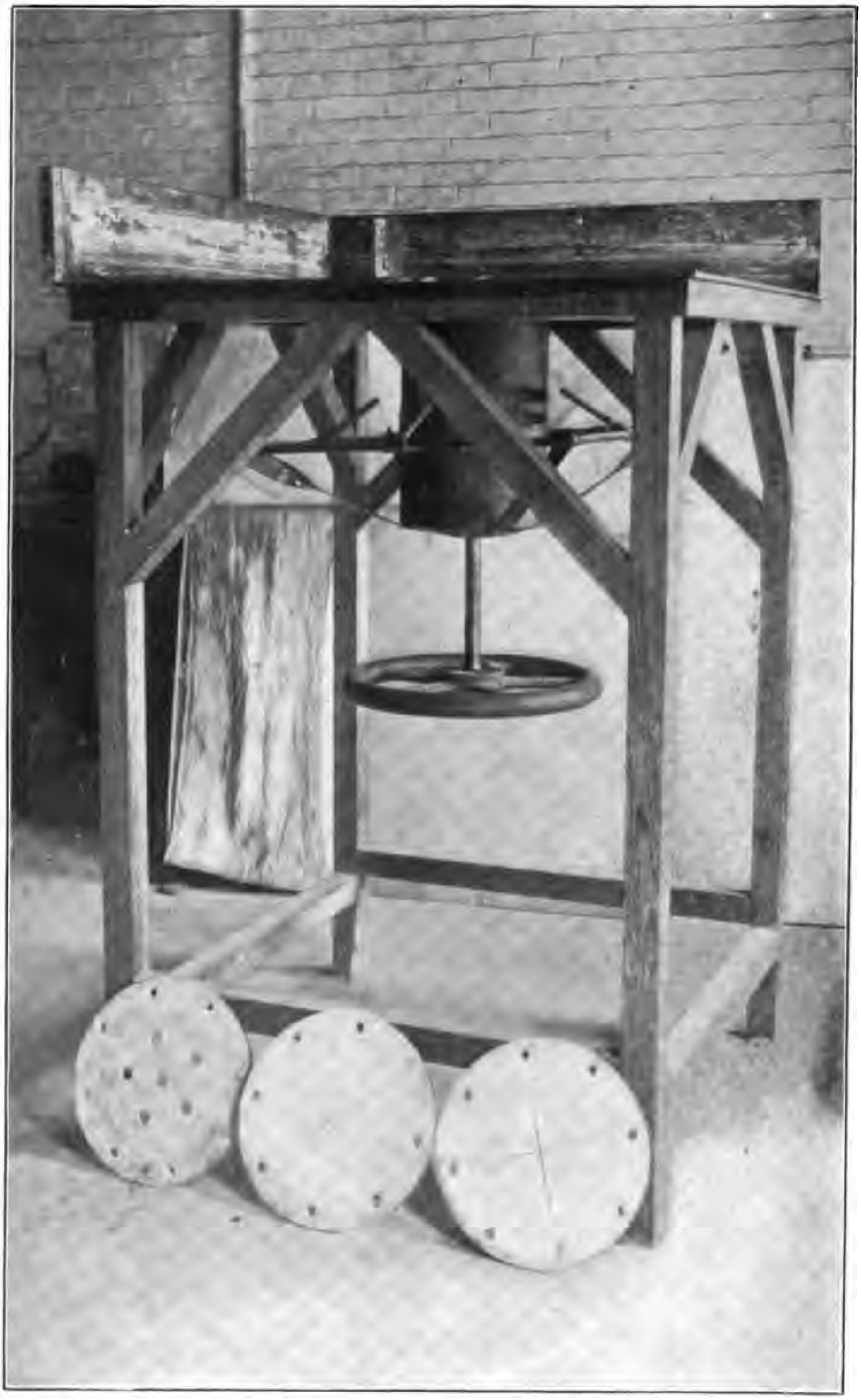
Before undertaking any very extensive experiments it seemed best to perform a few with the rather crude apparatus at hand. A small circular pan of tin, 2 feet in diameter and 3 inches deep, was employed to hold the sediments. It had a hole in the center in which a cork might be fitted and a smaller hole at the side to permit the water to be drawn off. The pan was half filled with water, the openings below being closed, and the following series of sediments were deposited in order from the bottom upward, in layers of somewhat variable thickness, to a depth of about 1½ inches:

13. Sand.
12. Marble dust and plaster.
11. Sand.
10. Coal dust.
9. Plaster.
8. Marble dust.
7. Sand.
6. Plaster.
5. Coal dust.
4. Marble dust.
3. Marble dust and plaster.
2. Coal dust.
1. Plaster.

After settling, the excess of water was drawn off and the whole was allowed to dry for twenty-four hours. This method was followed in all subsequent experiments and was found to be quite satisfactory. Next a perforated cork was substituted for the one already in the central aperture, and a glass tube was inserted in it, which in turn was connected by a rubber tube with a rubber bag containing a mixture of plaster and water and supported by boards between the jaws of a vise. The mouth of the bag was closed and the vise was slowly tightened until most of the plaster had been forced through the tubing into the sediments. The results of this experiment will be described in detail later (Exp. I, figs. 101 and 102). It is for the moment only necessary to state that the experiment was quite satisfactory as far as it went; but this and several others performed on the same apparatus, although more or less successful, showed that the scale was too small, that the method of injection was inadequate, and that the material used for injection was not to be relied upon, as there was no means of regulating its liquidity or viscosity and preventing its very rapid solidification.

CONSTRUCTION OF APPARATUS.

After some study of the good and bad points of the preliminary apparatus, the instrument figured in Pl. XLII, and in cross section in fig. 100 was constructed. The principal working parts of the apparatus are the sheet of boiler plate *a* (fig. 100), the cylinder *c*, the piston head *p*, the screw *s*, and the conduit plate *d*. The boiler plate,



MACHINE FOR INTRUSION EXPERIMENTS.

one-quarter inch thick and 3 feet square, is supported by the frame *f*. At its center was cut a hole of the same diameter as the inside of the cylinder, 8¼ inches. The cylinder, of cast iron, is bolted to the under surface of the boiler plate directly beneath the hole. Working in the cylinder is the piston head, composed of two beveled disks of cast iron, bolted together, the open space caused by the beveling being packed with hemp. This piston is forced up and down by means of a screw *s*, operated by the wheel *g*. The pitch of this screw is one-

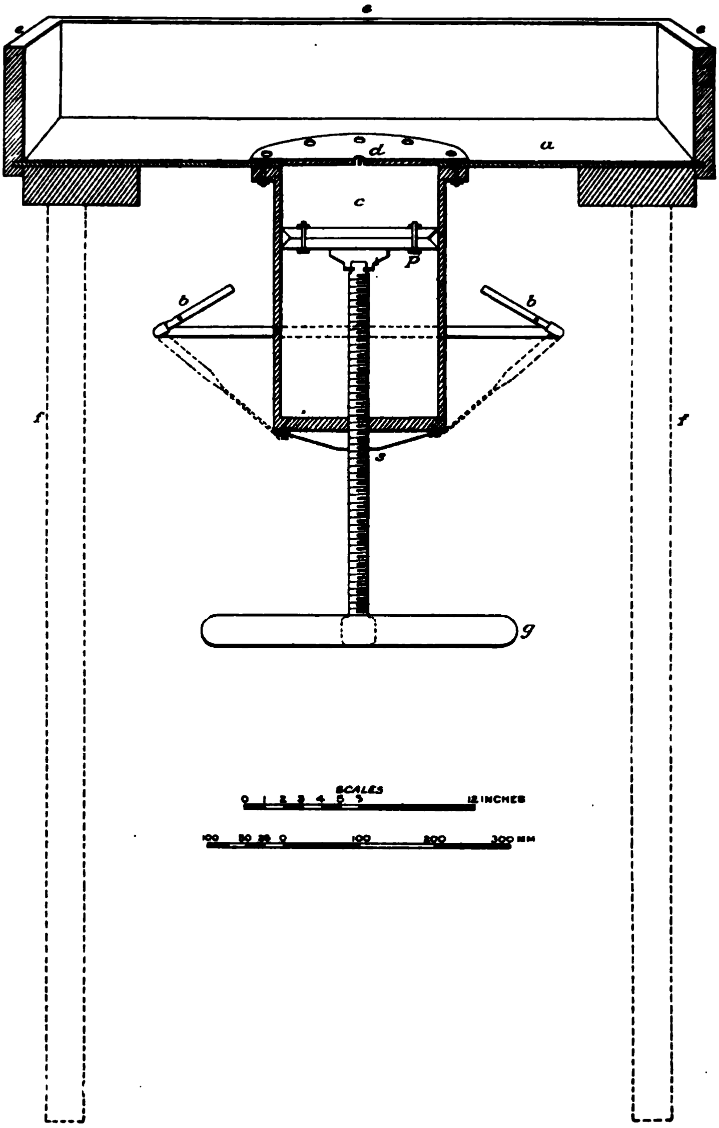


FIG. 100.—Cross section of intrusion machine.

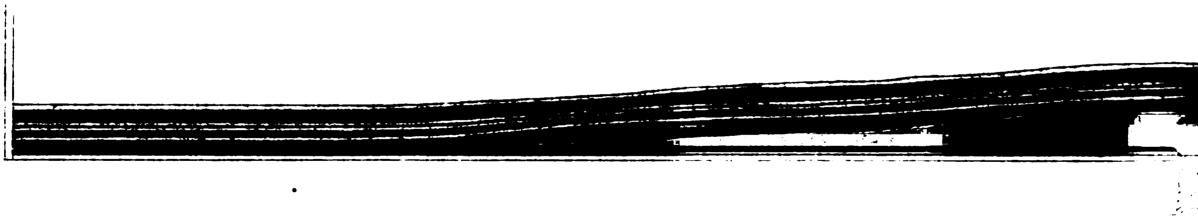
fifth inch. The conduit plate *d* is one of the three shown at the base of the apparatus in Pl. XLII. The first has a long, narrow slot cut through the center; the second has two of these slots intersecting at the center at right angles to each other, while the third has a series of 6 holes in which plugs may be screwed. Some of these plugs serve to close the apertures, while others are pierced or have small tubes of brass running through them and extending above the surface of the plate. By means of these plates conduits resembling fissures or of the hypothetical tubular form may be used. The method of operating the apparatus is as follows:

The piston is first brought down to its lowest point and the cylinder is filled with wax, which is melted by means of the Bunsen burners *b b*. The level of the wax is then brought to the top of the cylinder by advancing the piston a short distance, and one of the conduit plates is bolted to the boiler plate over the mouth of the cylinder. Next the grooved boards *e e* are fitted over the extending edges of the boiler-plate and their ends are screwed together. All joints or openings are painted with melted wax or paraffin to make them water-tight. The tank is then ready for receiving the sediments, which are deposited in the manner already described. This having been accomplished the excess of water is drawn off through a tap near the bottom of one of the boards. After the sediments have dried sufficiently the Bunsen burners are lighted and allowed to play on the cylinder for a few minutes longer than the time required to melt the wax, determined at the first melting. The gas is then turned off and injection is started by slowly turning the screw. As has been already said, the pitch of the screw is one-fifth inch and the inside diameter of the cylinder is 8¼ inches. Thus one complete turn of the screw would advance the piston one-fifth inch and a little over 10 cubic inches of material would be forced out of the cylinder, or for an advance of 1 inch of the piston 53 cubic inches of wax would be injected into the sediments. After the injection has been accomplished the sides of the tank may be removed and the model sectioned and photographed.

Of the following five experiments described the first two were performed by means of the preliminary apparatus and the last three with the special instrument.

EXPERIMENT I. IRREGULAR INTRUSIONS.

Process.—The sedimentary section has already been given for this experiment (p. 292). It was found later, on cutting the model after intrusion, that the individual layers were not so uniform in thickness as they should be, and especial attention was paid to this in all later experiments, more time being given for each layer to settle before the next was added, and greater care being taken to insure an even distribution of material.



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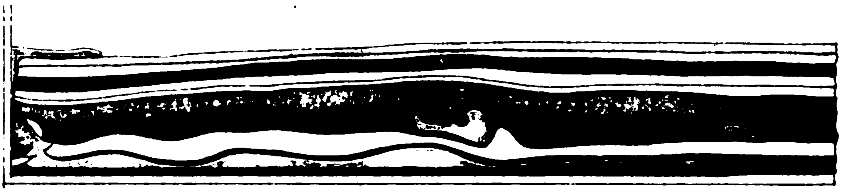

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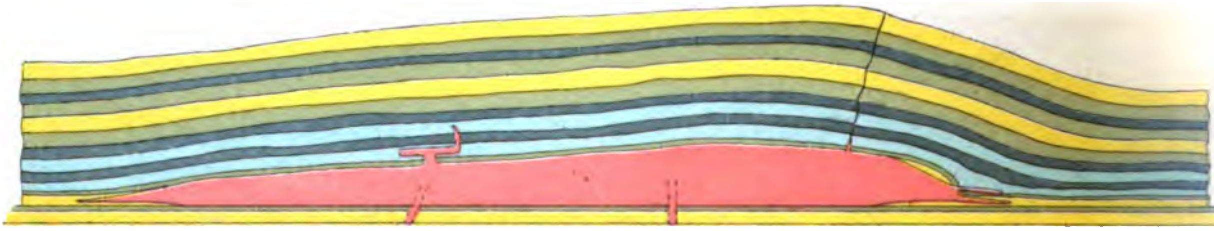

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CROSS SECTIONS OF E

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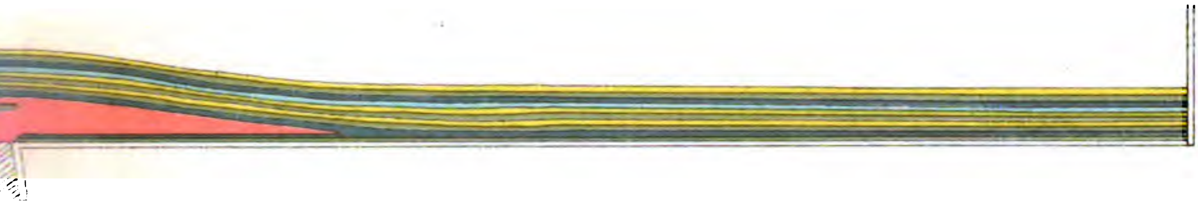

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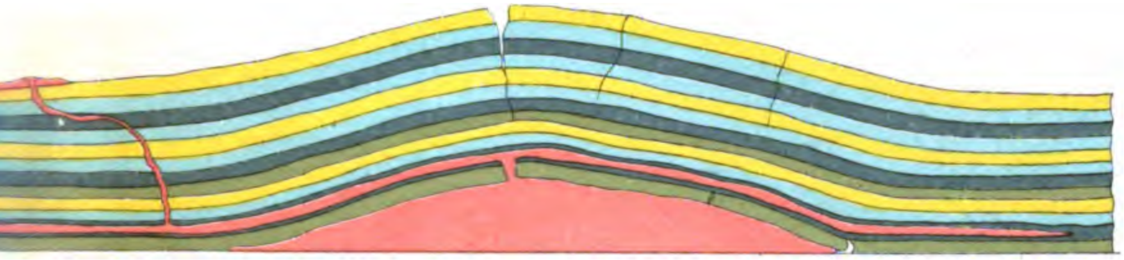

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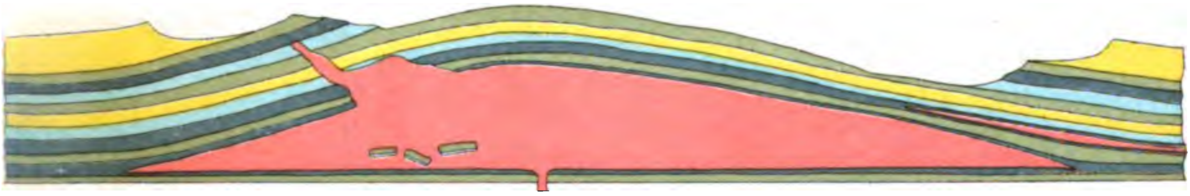

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XPERIMENTAL MODELS

RATING

ND EROSION

ST HOWE

0

ATION

☐ Sand ■ Coal ☐ Intrusive

JULIUS BIEN & CO. LITH. N.Y.

The plaster and water which was to be injected had about the consistency of thick cream, and was colored red to distinguish it from the plaster layers in the model. The time required for the intrusion was of necessity rather short, as the mixture of plaster and water solidified very rapidly. An even pressure was maintained by means of the vise for two minutes, at the end of which time most of the plaster had been forced into the model. Slight oscillation occurred on the surface during intrusion, but there was no fracturing and no marked doming. Just before injection was stopped the intrusive material broke through the sediments near the edge of the pan and flowed out on the surface.

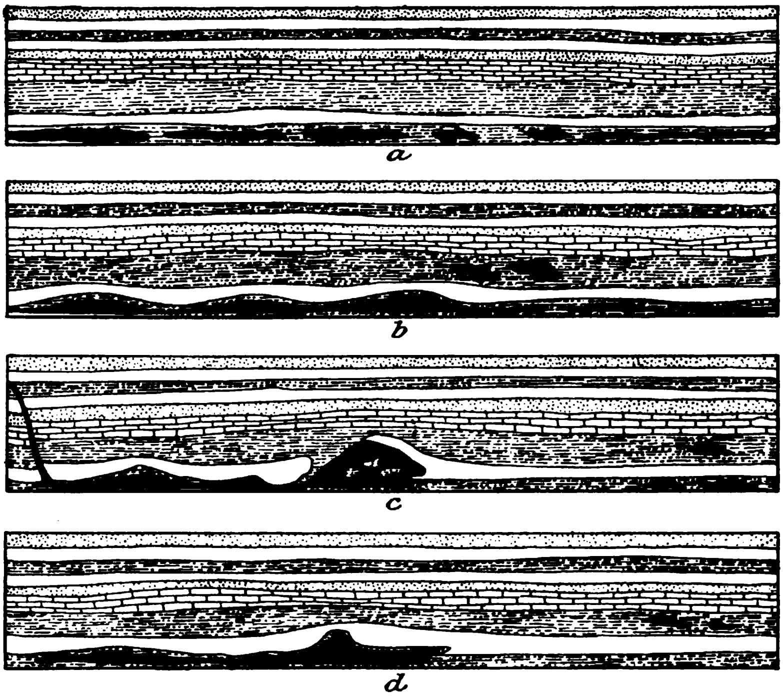


FIG. 101. Sections. Experiment I.

Cross sections.—As soon as the plaster had hardened the model was cut in sectors, the first to be removed being directly opposite the point where the plaster had flowed out. In this region it was found that the intrusive had spread as a thin sheet in the first coal-dust layer and extended continuously from the center about halfway to the edge of the pan. From this point sections were made at intervals of one-half inch at the perimeter (of which fig. 101, *a*, *b*, *c*, and *d*, and sec. 2 of Pl. XLIII are examples), and very soon marked variations were encountered. The intrusion was approaching nearer to the edge, and seemed to have entered the coal as fingers from the main sheet, small isolated patches being encountered as shown on the right-hand side of sec. 2 of Pl. XLIII and in *a*, *b*, and *c* of fig. 101. As the region of eruption was approached still greater irregularities occurred; several fingers of the intrusive were found in the second coal horizon, and considerable deformation of the adjacent beds was noted (*b*, *c*, and *d*, of fig. 101). Sec. 2 of Pl. XLIII is drawn from the edge of the pan at the point of extrusion, halfway to the center. It is more or less generalized, but will serve to bring out the several points characteristic of this experiment. It will be noted that above the horizon of massive plaster in the middle of the column practically no deformation has taken place, most of the irregularities being due to bedding, while the beds below have been much disturbed. Just below and to the right of the intrusion in the second coal horizon the marble-dust layer has been folded, and a little farther on (*c*, fig. 101) this fold develops into a fracture through which the intrusive has risen and forced its way as a finger into the stratum of coal dust. Near the edge another fracture occurred and through this the intrusive flowed to the surface. In the lower horizon of intrusion considerable variations in the thickness may be observed, and also a tendency to form local lenticular swellings.

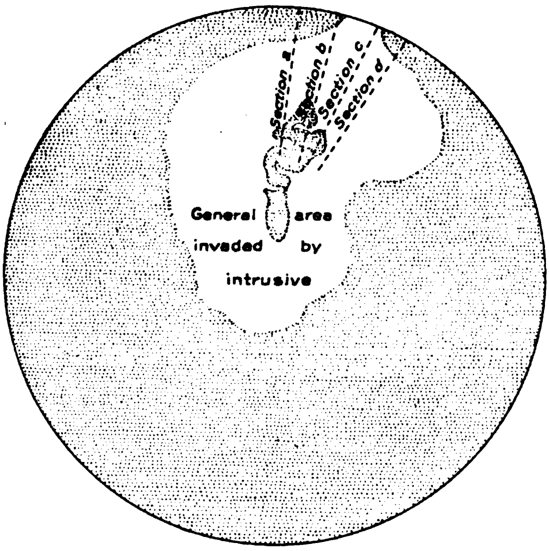
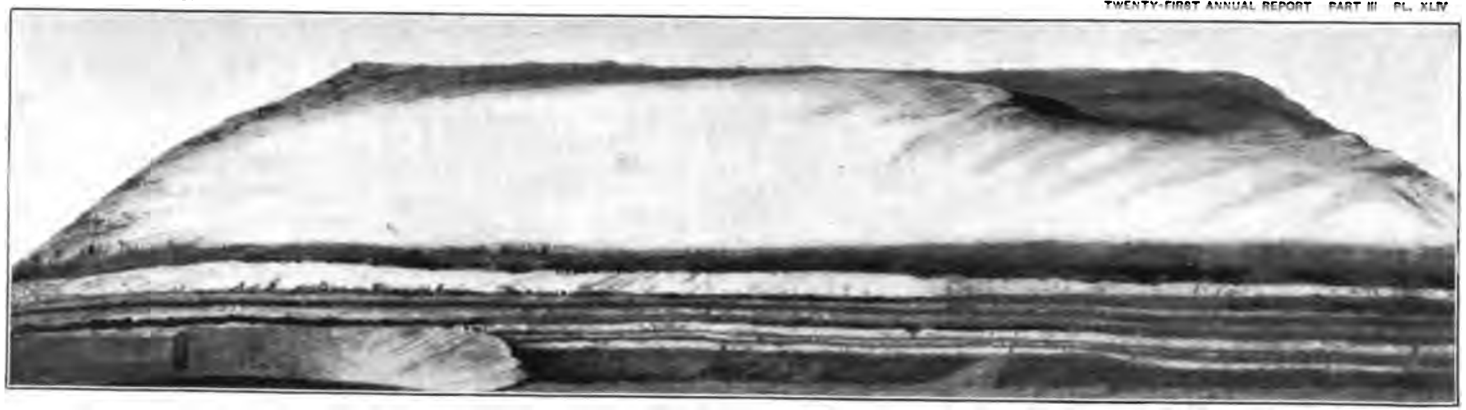


FIG. 102.—Ground plan of laccolith, Experiment I.

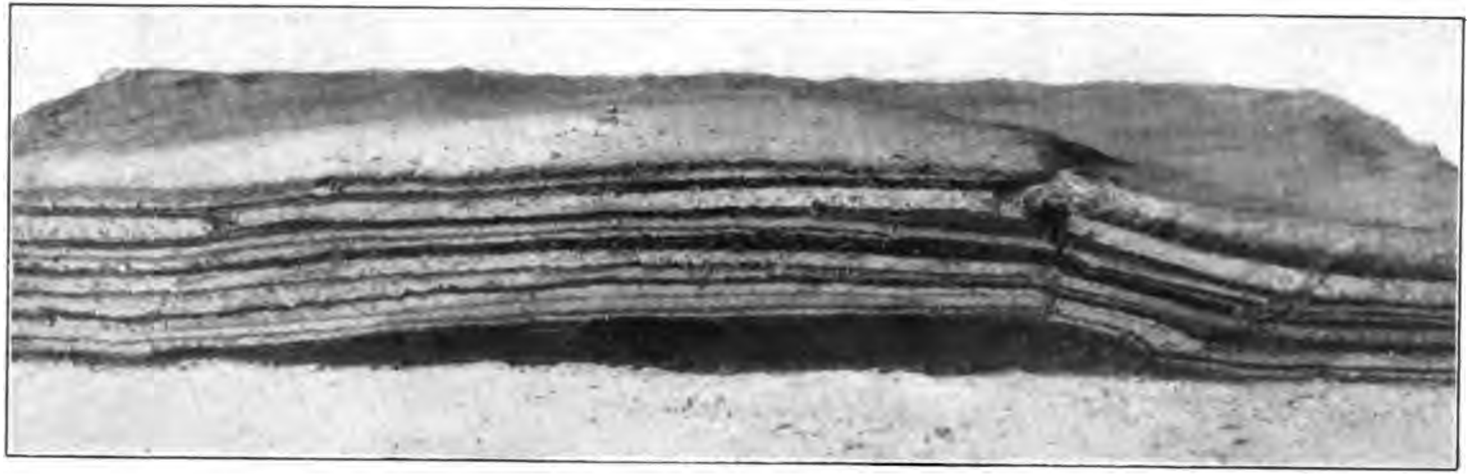
Ground plan.—The plan of the intrusion was roughly elliptical with the conduit at one of the foci (fig. 102). About the other focus was a region of coal dust into which the plaster had not intruded, apparently having flowed about it.

EXPERIMENT II. SYMMETRICAL LACCOLITH.

Process.—The results of the second experiment were in marked contrast to those of the one just described. The greater regularity in the form of the intrusion was in a large measure due to the nature of the sediments, there being more and thinner plaster layers than in the first series, and also thinner coal layers, the strata being therefore uniformly thin bedded and flexible. The result was that the pressure brought to bear on the overlying beds by the intruding magma was



A. UNSYMMETRICAL LACCOLITH, SURFACE OF MODEL, AFTER INTRUSION WITHOUT LOAD.



B. CROSS SECTION OF UNSYMMETRICAL LACCOLITH.

uniformly distributed and transmitted with little or no loss by lateral deformation to the very top of the column. In the first experiment the overlying coal layers were so thick and so loosely compacted that the upward pressure expended itself solely in compressing the strata, or in pushing aside and rearranging the individual grains of coal. The conditions of intrusion were the same in both experiments, but in Experiment II injection was accompanied by a gentle doming about the center, with resulting radial fractures.

Section.—A section of this model is shown in Pl. XLIII. The symmetry of the laccolith and the relation of the overlying beds to it are well shown, and were almost as diagrammatic in the original as they are in the figured section. One interesting point was the horse of plaster which was carried up from the basement layer of plaster and floated in the magma (compare Dome Mountain, Pl. XXI, section D–E; also Carriso Mountains, fig. 81, p. 210). The following is the order in which the sediments were deposited, the total thickness being about half an inch:

10. Sand.
9. Plaster.
8. Coal.
7. Marble.
6. Sand.
5. Plaster.
4. Sand.
3. Plaster.
2. Coal.
1. Plaster.

The remaining experiments were all performed by means of the special apparatus.

EXPERIMENT III. EXTRUSION, SILL, AND LACCOLITH.

Process.—The conduit plate with the single slot was in place and the bottom of the tank was covered with plaster to make a smooth surface flush with the plate, and the tank was partly filled with water. The following series of sediments were then deposited to the depth of about 2.5 inches:

12. Sand.
11. Marble.
10. Coal.
9. Marble.
8. Sand.
7. Marble.
6. Coal.
5. Plaster.
4. Sand.
3. Marble.
2. Coal.
1. Plaster.

Previous to the deposition of the sediments the cylinder had been filled with a mixture of beeswax, paraffin, and ozokerite. It was found that thirty minutes were required to melt this mixture.

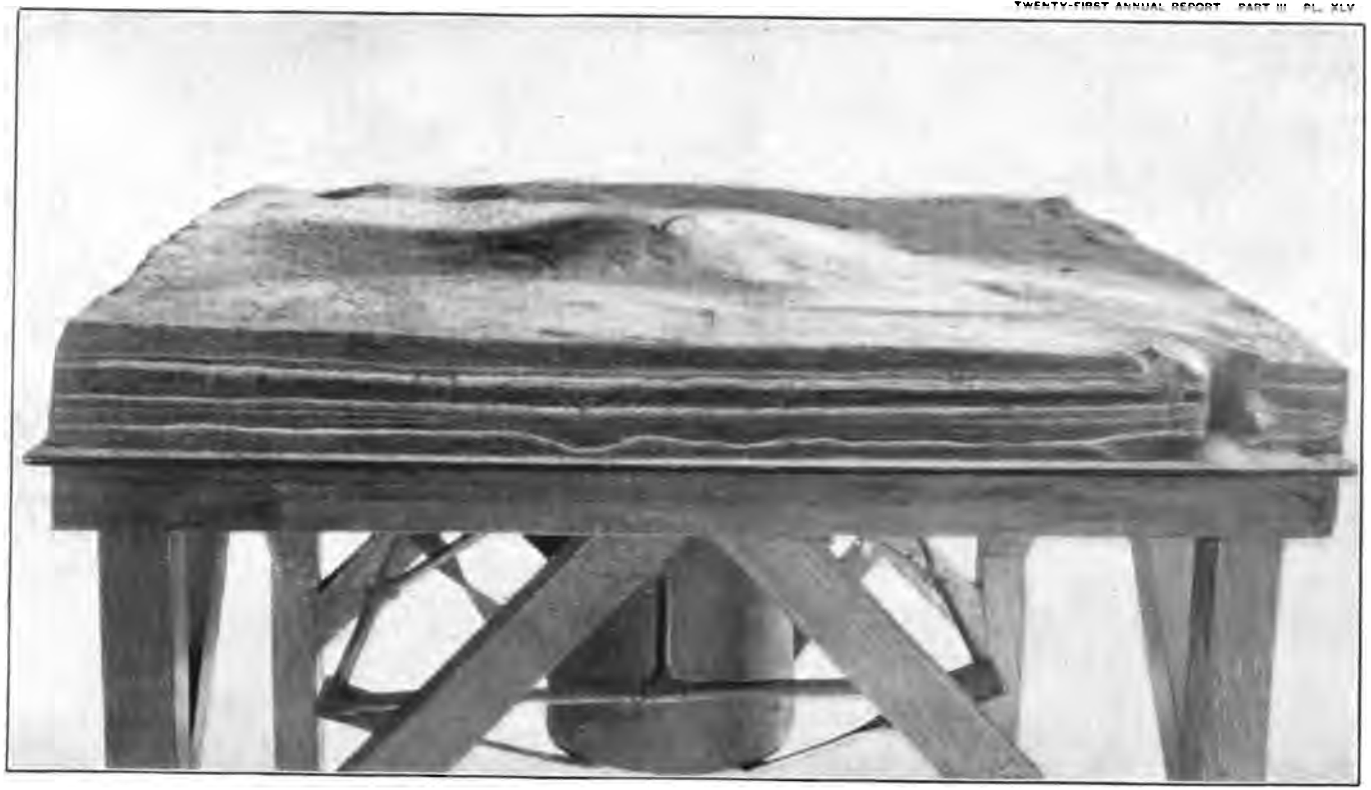
After the sediments had been allowed to dry for forty-eight hours the wax was melted and injection started. The piston was advanced 4 inches in fifteen minutes, at the end of which the whole model was gently domed. Several radial fractures had developed about the center, and part of an encircling fracture was also formed. The piston being advanced farther two-fifths inch, wax began to flow from the intersection of one of the radial fractures with the encircling fracture. The eruption continued for about five minutes, a small wax cone being formed, and the excess of wax flowing off in four or five well-defined streams. A further slight advance of the piston started the wax again, and after it had stopped flowing for the second time the whole mass was allowed to cool and solidify for twenty minutes. At the end of this period the piston was advanced 1½ inches in twenty minutes. By this time the wax had become extremely viscous, and the result was a small steep dome directly over the conduit, accompanied by circular fracturing.

Sections.—When the wax had thoroughly cooled, sections of the model were made, the most typical one being through the top of the dome and cutting the conduit through which the wax had risen to the surface and had overflowed. This section (sec. 3, Pl. XLIII) showed that the wax first intruded had entered the lowest layer of coal dust, had spread out as a sheet or sill, and had broken up through certain fissures, saturating the absorbent layers of coal and sand locally; on reaching the surface it flowed out, forming a miniature volcano. The second intrusion did not rise above the first sill, but lifted it and the first plaster layer, fracturing the beds above, but not causing any break in the sill. The effect of wax coming through the fissure-like conduit was to give the base of the laccolith a somewhat elliptical outline, the longest diameter being in line with the conduit. This experiment brought out in an interesting manner the tendency of a magma when extremely liquid and rapidly injected to form sheets or sills, and when more viscous to form laccolithic bodies. Two distinct types of fracturing in the overlying sediments were noted, the one of fractures concentric about the center of the dome, the other of fractures radiating from the center of the dome. Fracturing according to the first type will begin in the beds immediately above the intrusive at the point where its surface is concave and where the sediments are being folded into an encircling monocline. Fracturing according to the second type will begin at the apex of the domed sediments.

EXPERIMENT IV. UNSYMMETRICAL LACCOLITH.

Process.—In Experiment IV the conduit plate having six holes was used with two conduits extending above the level of the plate. One was vertical, while the other was inclined at an angle of 60 degrees with the horizon in the direction of the first—i. e., its walls dipping away from the first. The bottom was covered with sand until its surface was flush with the top of the conduit plate, then water was introduced and the sediments were deposited in the following order:

20. Sand.
19. Plaster.
18. Sand.
17. Coal.
16. Plaster.
15. Marble.
14. Sand.
13. Marble.
12. Sand.
11. Plaster.
10. Sand.
9. Coal.
8. Plaster.
7. Coal.
6. Plaster.
5. Marble.
4. Sand.
3. Plaster.
2. Sand.
1. Plaster.



DOMED SURFACE OF MODEL; INTRUSION UNDER LOAD.

Superficial doming.—The injection in this experiment was very slow, one complete turn of the wheel being made in three minutes. There was no apparent doming at the surface until after the piston had been advanced 4 inches, but from this point on a very well-defined unsymmetrical dome began to form. As will be seen in *A* and *B* of Pl. XLIV, there is a gentle upward slope from the left, which continues well past the center of the model, while to the right the rise to the summit is very abrupt. The high angle of this slope was accentuated by the fracture indicated in sec. 4 of Pl. XLIII. The strata to the left of this fracture were lifted by the force of intrusion and made a well-defined fault scarp, which was very striking during the process of injection, but which soon became obscured by the sifting in of dry sand at the surface. This main fracture was the only one noted during the intrusion, but several other minor ones were discovered on cutting the model.

Sections.—Pl. XLIV, *B*, and sec. 4 of Pl. XLIII, illustrate fairly well most of the interesting points of this experiment. In all the other experiments the wax spread out in a layer of coal dust, corresponding to shales in nature, but in this case the main intrusion was in the horizon of sand over the first plaster layer. Just above the inclined conduit in the colored section a peculiar mushroom-shaped body of wax is seen, and another, not shown in the diagram, was found over the second conduit. Evidently the upper edges of the conduit tubes were somewhere in the middle of the first marble-dust horizon when injection was started, and the wax, finding the intrusion difficult in the closely-packed marble dust, flowed downward and spread out in the underlying sand layer, and subsequently lifted all the overlying beds. These projecting conduit tubes are necessarily artificial in their relations to the sediments and are unlike anything in nature. A number of small dikes occurred, filling local fractures, but the main intrusion was purely laccolithic. One characteristic which this experiment shares in common with the first is the mashing of the marble dust at the extreme right of the laccolith. The plaster immediately below has been fractured and the right-hand portion has been faulted upward half an inch above its original position, but the plaster layer next above has not been involved in this movement. The intervening layers of coal and marble dust, because of the lack of cohesion of their individual particles, have been pushed aside and have not transmitted the force coming from below to the overlying beds. The point to be particularly noted in this experiment is the asymmetry of the dome and its relation to the inclined conduit. A magma rising through an inclined conduit tends to form an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical. Such an inclined conduit corresponds with the case of inclined dikes following Algonkian lamination upward to the Cambrian unconformity (see Chap. II, pp. 203–204).

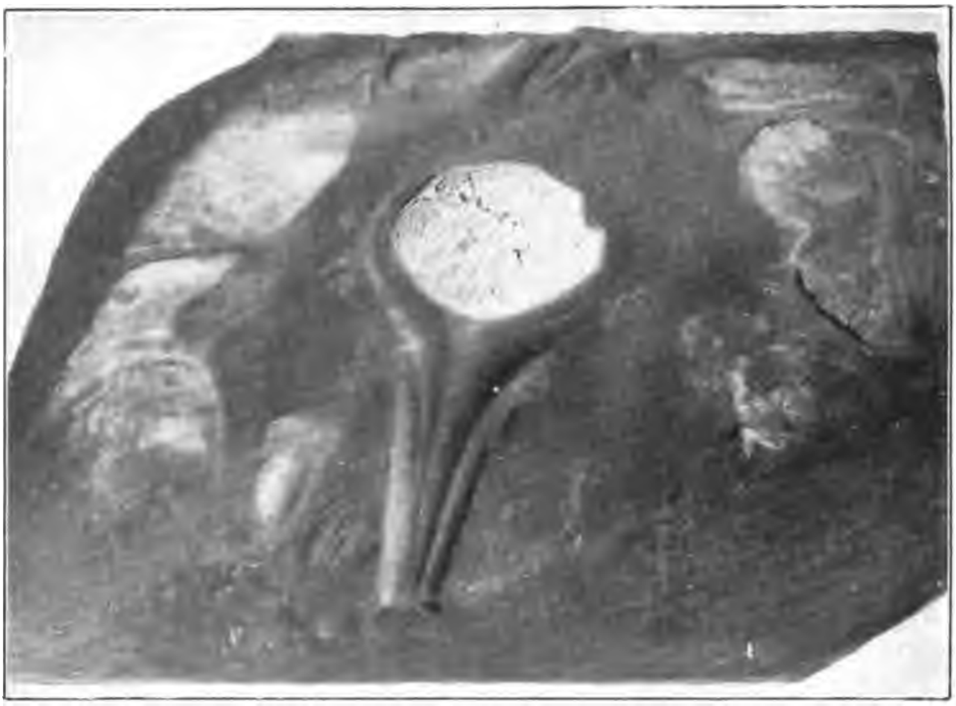
EXPERIMENT V. EFFECT OF LOAD AND OF EROSION.

Intrusion.—As it was intended to try the effects of artificial erosion on the laccolith formed in this experiment, special arrangements were made to facilitate the transfer of the model from the injection apparatus to the erosion tank. The conduit plate having six holes was used, all the holes but the central one being closed. This was left as a simple circular opening without any projecting tube. When this plate had been bolted in place sand was added, as usual, until it was level with the top of the plate. A sheet of zinc 35 inches square, having a hole in the center to correspond with that in the boiler plate, was then laid in place. The purpose of this sheet of zinc was to supply some sort of support for the model while it was being slid from the injection apparatus to the board on which it was carried to the erosion tank. The zinc having been placed in position, water was added, and the sediments were deposited as follows:

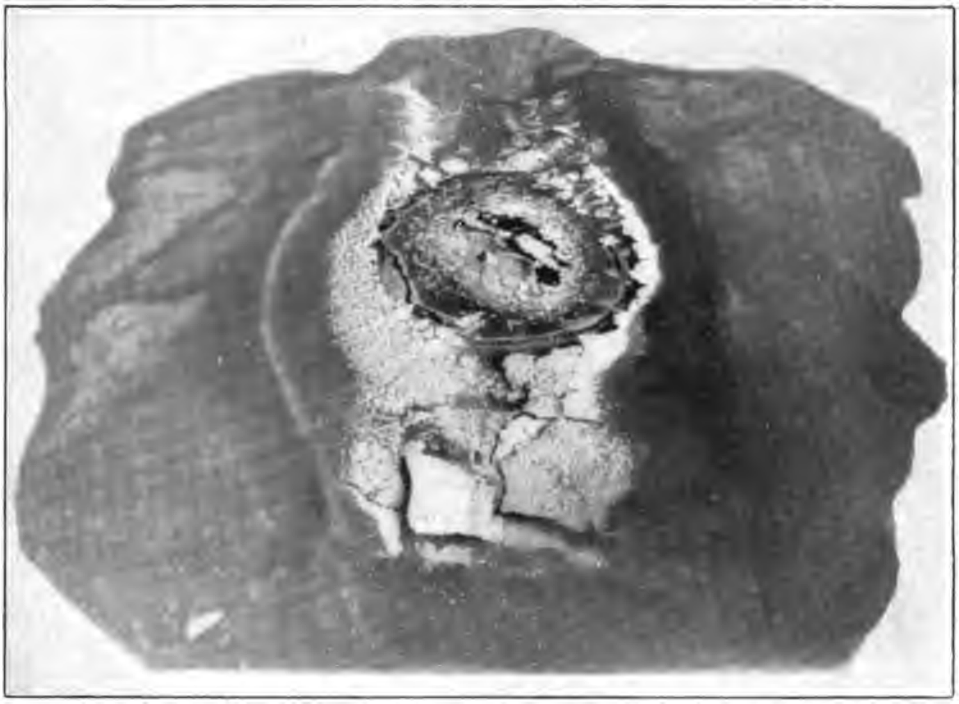
23. Sand.
22. Marble.
21. Plaster.
20. Marble.
19. Sand.
18. Marble.
17. Coal.
16. Marble.
15. Sand.
14. Plaster.
13. Marble.
12. Coal.
11. Marble.
10. Sand.
9. Plaster.
8. Marble.
7. Coal.
6. Plaster.
5. Marble.
4. Coal.
3. Marble.
2. Sand.
1. Plaster

After the sediments had dried somewhat, a cloth was placed over them and 300 pounds of shot, to simulate load of superincumbent sediments, were evenly distributed over the surface. The wax was then melted and allowed to cool for forty-five minutes before injection was started. This was to insure viscosity. The piston was then advanced 5 inches, the speed averaging 1 inch in fifteen minutes. At the end of the injection the wax had become very hard and it was impossible to force any more into the model. When the shot was removed it was found that a very symmetrical dome had been formed (Pl. XLV), with one distinct fracture crossing the dome at its summit.

Erosion.—The model was then transferred to the erosion tank, great care being taken not to cause any further fracturing of the sediments. A few fractures indeed developed at the sides and corners, but they were not of sufficient importance to affect in any way the process of erosion. The erosion tank, 6 feet square and 1 foot deep, had a special flood gate by means of which the water level might be kept constant or changed at will. The water which was to accomplish the erosion was supplied in the form of a fine mist. By means of a small perforated nozzle, several jets of water were thrown with some force against a fine-meshed sieve, with the result that a large part of the water passed through and became atomized. As a certain amount of drip from the sides of the sieve accompanied the process, it was found



A. EROSION OF EXPERIMENTAL LACCOLITH (FIRST STAGE).



B. EROSION OF EXPERIMENTAL LACCOLITH (SECOND STAGE).

necessary to place the spraying apparatus at one side of the model instead of directly over its center. The shower was arranged so that the bulk of the water fell at the center of the model, but some particles of water were carried beyond, while others fell short, the result being that there was a zone of maximum rainfall extending from one side of the model to the other and passing over the dome. This necessarily influenced the drainage. As shown in Pl. XLVI, *A* and *B* representing an earlier and a later stage of degradation, two main streams developed in the line of maximum rainfall, flowing in opposite directions from the dome, and in a very short time after erosion commenced they had captured all the drainage, which, as shown in Pl. XLVI, *A*, was initially radial. Several small streams consequent upon the initial slope flowed from the dome and united near its base to form the four encircling master streams. Two of these master streams on each side united and formed the two trunk streams which drained the whole region. The action of frost and the disintegration of rock due to the chemical action of surface water could not be imitated, but similar results were brought about by the impact of the fine particles of water on the various layers of sand and plaster and coal. The force of the descending mist was indeed sufficient to cause a breach at the summit of the first plaster layer exposed, long before the streams had cut into the plaster on the flanks. Notwithstanding these unnatural conditions, revet hills were formed which were not unlike those found in nature. By the time that the first layer of plaster had been removed a dike was exposed at the left of the summit (Pl. XLVII, *A*), which had risen through the main fracture shown in Pl. XLVI, *A*. This dike of wax was not acted upon by the water and served to protect the left-hand side of the dome, deflecting a large part of the drainage to the right. The result is shown in Pl. XLVII, *A* and *B*.

Sections.—Sec. 5 of Pl. XLIII shows the form of the intrusive in this experiment, which was in many ways the most interesting. The laccolith proper was intruded into a layer of coal dust, as was the sheet which rests above the main intrusion to the right. In the body of the laccolith are three horses of plaster which belong to the horizon resting above the intrusive. It seems likely that in the early stages of intrusion fracturing occurred in the immediate neighborhood of the fragments of plaster, and that the wax rose above these and entered the main fissure, forming the dike, first following an encircling fracture and later a radial one.

SUMMARY OF EXPERIMENTS.

I. Variations dependent on the passive agents.

1. If the strata immediately above the intrusive are lacking in rigidity and are of considerable thickness, they will not transmit to the overlying beds the deforming force of the intrusion, but will themselves be locally deformed and will cause this force to expend itself laterally.

2. The converse is also true. If the overlying sediments are comparatively rigid they will tend to transmit the deforming force of the intrusion uniformly in lines normal to the surface of the intrusive.

3. The least coherent strata are the ones in which intrusion is most likely to occur.

4. Thick beds of incoherent material favor the production of intrusive bodies of irregular form.

5. For the same viscosity of magma (Experiments IV and V, Pls. XLIV, *A*, and XLV) it is probable that the domical curvature of a laccolith, other things being equal, varies with the load, and hence with the thickness of superincumbent strata. That is, a greater load produces a higher dome of smaller ground plan for the same volume of intrusive material (see paragraph below, numbered 3.)

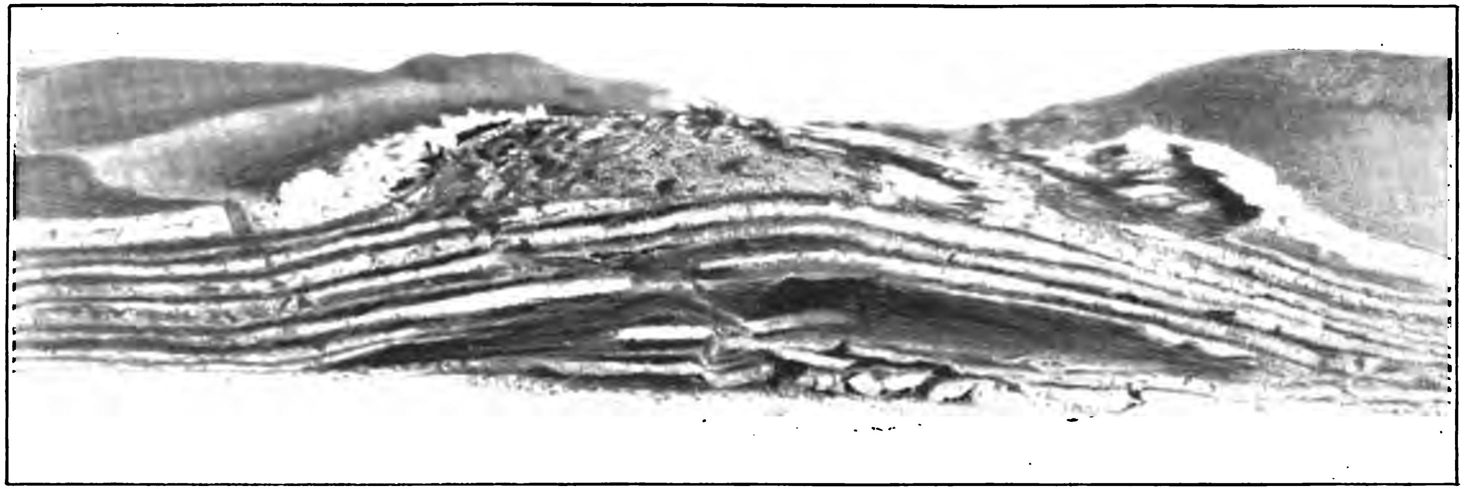
6. Any stratigraphic obstacle to horizontal spreading (Experiment I, fig. 2 of Pl. XLIII) may cause a sill to thicken locally into domes, the loci of these domes being determined by points of weakness in the overlying beds. The thinner and more flexible portions of the superjacent competent stratum under coal dust are the points of greatest doming in model 1 (sec. 2 of Pl. XLIII).

7. A magma rising through an inclined conduit tends to form an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical (sec. 4 of Pl. XLIII).

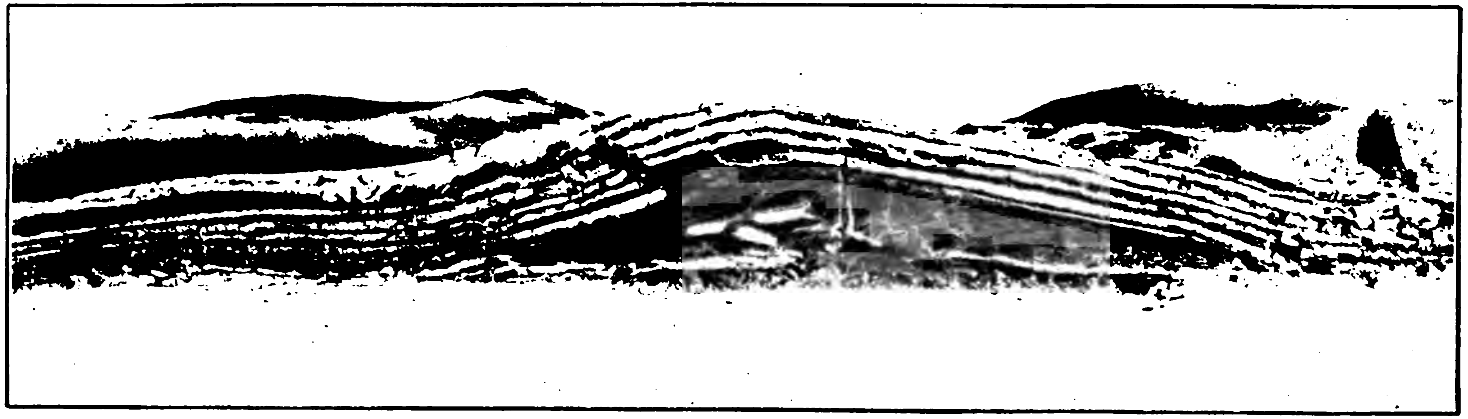
8. Fractures initially radial and secondly concentric tend to form in frangible strata over a symmetrical dome, the radial fractures gaping upward and the concentric ones downward. Hence the latter are the first to give passage to the intrusive, which, through them, forms peripheral sills, or, in connection with the radial fractures, dikes. Over an unsymmetrical dome, overthrusting and escape of magma to higher horizons will take place in the direction of greatest thickness of the dome (Pl. XLIV, *B*, and sec. 4 of Pl. XLIII).

II. Variations dependent on the active agents.

1. If the magma is in a condition of considerable fluidity it will tend to spread as a thin sheet in some stratum of least resistance (sec. 3 of Pl. XLIII), and, conversely,



A. CROSS SECTION OF ERODED DOME.



B. SECOND SECTION OF DOME SHOWN IN *A*.

2. If the magma is viscous it will tend to form a true laccolith, with its horizontal extension restricted and its thickness increasing toward the center.

3. For the same load (Experiment III) it is probable that the domical curvature of a laccolith, other things being equal, varies with the viscosity (see paragraph numbered 5, above). That is, a more viscous magma produces a higher dome of smaller ground plan for the same volume of intrusive material (sec. 3 of Pl. XLIII).

4. A viscous magma injected rapidly probably tends to form a dome of smaller radius, other things being equal, than when injected slowly (Experiments III and IV).

In the experiments described the injected wax was permitted to break its way into the sediments. The analogies to be drawn from these experimental illustrations should therefore be confined to cases of deformation directly due to the intrusive (see Chapter I, pages 187–188). No attempt was made in the experiments to imitate concomitant regional deformation.

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